



MIDOCEAN UNIVERSITY

College of Management

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**Supporting Runway Maintenance Decisions Through Integrated Analysis of
Friction Trends, Flight-Traffic Characteristics, and Rubber Removal Practices:
An Applied Study on Saudi Airports**

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إهداء

إلى والديّ الكريمين،

الذين لم يكونا مجرد داعمين، بل كانا الأساس الذي استندت إليه في كل خطوة،
غرسا فيّ الثبات حين يتزعزع الطريق، ومنحاني اليقين حين تتعدد الاحتمالات،
فكان عطاؤهما ممتدًا كأفق لا ينتهي، وأثرهما حاضرًا في كل إنجاز.

وإلى زوجتي وأبنائي،

الذين لم يكونوا شهودًا على هذه الرحلة فحسب، بل جزءًا أصيلًا منها،
تحملوا انشغالي، وشاركوا صمتي، واحتضنوا طموحي،
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وإلى كل من آمن بي في مراحل لم تكن النتائج فيها واضحة،
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تم تطبيق الدراسة على أحد المطارات الدولية في المنطقة الغربية من المملكة العربية السعودية، باستخدام منهج تحليلي كمي قائم على بيانات تشغيلية حقيقية تمتد لقرابة ثلاث سنوات (فبراير 2023 – يناير 2026)، شملت تقارير اختبار الاحتكاك، وبيانات الحركة الجوية، وسجلات إزالة المطاط، وملاحظات حالة الرصف.

أظهرت نتائج التحليل وجود نمط تدهور متعدد المراحل لسطح المدرج، يمكن تصنيفه إلى ثلاث مراحل رئيسية: مرحلة الأداء المستقر، تليها مرحلة التدهور المتسارع، ثم مرحلة التدهور الهيكلي. كما كشفت الدراسة عن ظاهرة "دورة التدهور المركبة"، حيث تؤدي عمليات إزالة المطاط المتكررة إلى تآكل تدريجي في سطح الرصف، مما يقلل من فعالية عمليات الصيانة اللاحقة ويُسرّع من معدل التدهور.

بناءً على ذلك، تقترح الدراسة إطاراً متكاملاً لدعم اتخاذ القرار يتكون من خمسة عناصر رئيسية تشمل: مراقبة الحركة الجوية، تحليل اتجاهات الاحتكاك، تقييم حالة الرصف، منطق اتخاذ القرار، وآليات التغذية الراجعة.

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الكلمات المفتاحية: احتكاك المدرج، إزالة المطاط، صيانة المدارج، الحركة الجوية، دعم القرار، المطارات السعودية.

ABSTRACT

This study develops a comprehensive decision-support framework for runway surface maintenance by integrating friction trend analysis, flight-traffic characteristics, and rubber removal practices. Applied to a major Saudi international airport, the research employs a quantitative, longitudinal, documentary analytical approach using operational data spanning approximately three years (February 2023 to January 2026).

Data sources included ten friction test reports from a certified ASFT vehicle, twenty-eight months of air traffic data, rubber removal records, and pavement condition observations. The findings reveal a three-phase pavement lifecycle model: a healthy phase (2023), an accelerated degradation phase (2024), and a structural deterioration phase (2025–2026). A compounding degradation cycle was documented whereby repeated rubber removal operations progressively eroded the pavement surface, producing diminishing returns in each successive maintenance cycle.

The degradation rate appears to have increased from approximately -0.006μ per 1,000 landings in Phase 1 to approximately -0.014μ per 1,000 landings in Phase 2, while post-removal friction recovery declined from 0.89μ to 0.76μ across successive rubber removal events. By Phase 3, the pavement had deteriorated to the point where rubber removal could no longer be safely performed, leaving the runway in a state of irreversible friction decline.

The proposed decision-support framework comprises five integrated components: traffic monitoring, friction trend analysis, pavement condition assessment, maintenance decision logic, and feedback calibration. This study provides a scientific foundation for transitioning from reactive to predictive maintenance in runway surface management.

Keywords: runway friction, rubber removal, runway maintenance, air traffic, decision support, Saudi airports

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Chapter 1 INTRODUCTION

1.1 Background of Study

Safe aircraft landing and takeoff depend heavily on the runway friction. Airplanes need the friction between their tires and the runway to stop, stay on course, and slow down after touching down. But when the runway is wet, friction is reduced, and that's when things can go wrong. The risk of the plane going off the runway increases, and that can happen in a few ways - it can overrun, undershoot, or veer off. These kinds of accidents are still the most common type of aviation accident worldwide, according to the International Air Transport Association. That's why managing runway friction is so important for airport safety, and it's not just a maintenance issue, but a key part of keeping everyone safe.

The overall safety trend for aviation has been positive over the past few decades. However, this does not change the fact that the safety threat posed by runway excursions is still present and real. The IATA 2025 Safety Report identified the risk of a runway excursion as the greatest safety risk for aviation across all regions, a threat that has been present for the past decade. Flight Safety Foundation data reports 117 accidents involving an airliner in a runway excursion worldwide from 2017 through 2022. Of these accidents, approximately 80% occurred during a landing operation. The two most reported factors were unstable approaches and failure to perform a go-around. Additionally, inadequate runway surface friction was a reported cause of runway excursions, particularly in wet weather.

Runway excursions are one of the four high-risk accident categories defined in the Global Aviation Safety Plan by ICAO (2023). The available data for occurrences for this type of safety event over the last 13 years indicate that 748 runway excursion occurrences were reported worldwide, of which 490 were classified as accidents and 448 fatalities resulted. From a safety perspective, the tire-runway interface remains a pertinent issue, as previously discussed, and a safety-enhancing issue for air operations from paved surfaces. This is a long-standing issue but one that has ongoing relevance. Runway surface management is still a current and measurable safety issue for aviation.

The friction between a runway and an aircraft's tires is affected significantly by two different scale dimensions of the texture of the pavement surface, microtexture and macrotexture. The microtexture consists of the roughness of individual aggregate particles with characteristic wavelengths less than 0.5 mm. At slow speeds, this fine scale roughness comes into contact with the tire and develops large levels of adhesive friction. The macrotexture consists of larger scale roughness with characteristic wavelengths from 0.5 to 50 mm and serves to drain water away from the tire-pavement contact area at high speeds to prevent hydroplaning. Both the micro- and macrotexture deteriorate with time due to traffic, weather, and deposition of rubber stripped from tires of departing aircraft.

One of the biggest challenges to effective friction management on airport runways is managing the deposits of rubber from aircraft tires. Every time an aircraft lands, it deposits about 500-700 grams of rubber on the runway surface. Larger aircraft (wide-bodies) have even greater loads, thus creating an even larger footprint of rubber on the surface. The tire itself is made of rubber that reaches extremely high surface temperatures in a very short period of time, often in a split second transitioning from being stationary to full flight speed (about 240-300 km/h). This hot rubber melts, polymerizes upon cooling, and adheres hard to the pavement surface, creating a build up of surface material. This material reduces skid resistance, creates uneven wear, and is difficult to clean from the pavement surface.

The hardened film of rubber adheres to the pavement surface, and is difficult to remove. Clean up of rubber deposits from the pavement surface typically requires a significant amount of time and effort. In most cases, specialized equipment is required to remove rubber deposits. Some runways require special handling of different types of rubber from different aircraft tires (made from different compounds of rubber). Specialized cleaning equipment such as dedicated rubber removal machines, specialized sweeping machines, and high pressure washing units are typically required for this type of clean up. As with other airfield maintenance activities, significant resources are required for clean up, and much of this work is typically conducted outside of normal operating hours. Managing the buildup and clean up of rubber deposits from aircraft tires has become an important challenge in airfield maintenance management. Previous studies reported thousands of landings depositing tons of rubber on airport surfaces. These

landings create a continuum of rubber contamination over a length of 600–900 m from touchdown. This contamination progressively fills both the microtexture and macrotexture of pavement surfaces, smoothening the surface, filling the aggregate texture, and thus preventing effective drainage flow and the formation of a water film on the surface. This becomes a serious problem in wet weather conditions where adequate friction is necessary for safe aircraft operations (De Luca et al., 2016).

There are three main methods used to remove rubber from airport surfaces: high-pressure water-blasting, chemical treatment, and shot-blasting. While each process has its advantages and disadvantages, they all put a lot of stress on the pavement structure. This stress can cause the exposed surface layer to delaminate, dislodge adjacent aggregate, and cause micro-cracking in the existing pavement structure that reduces its life cycle. Each process requires trade-offs to maximize friction while ensuring safety and maintaining pavement life cycle. However, optimising such a critical process is very difficult. The typical approach for removing rubber from airport pavements is reactive, driven by recent traffic volume and friction loss. In reality, there are a variety of factors that affect friction, pavement degradation and traffic, and a more holistic approach is needed to develop an effective process for removing rubber from airport pavements.

Aviation industry in the Kingdom of Saudi Arabia is facing general challenges affecting aviation globally. In addition to these challenges the aviation sector in the Kingdom of Saudi Arabia faces its own specific needs. Saudi Arabia's National Vision Model Vision 2030 is a strategic outline of gains that the Saudi government will reap from efforts made and to launch a new era of scientific and scientific renaissance for Saudi Arabia and for the region, to cater to the needs of citizens and residents alike to improve quality of life and to enhance competitive global position. The Aviation Sector is one of the pillars of Saudi Vision 2030. Oliver Wyman projects that the volume of passengers using Saudi airlines will triple to 330 million plus flights to 250 plus destinations, with 100 plus aviation related entities operating 1,200 plus aircraft by 2030. Major investments expected in aviation related developments in new airport terminals, aircraft parking bays and support facilities, in addition to other related investments. Saudi Airports handled more than 128 million passengers in 2024, showing an increase of 15% compared with 2023 and 25% above pre-pandemic level

creating phenomenal pressure on new and existing airside developments and dedicated asset care and maintenance strategies.

Saudi Kingdom's airports are not only for general civil use but also serve for the annual Hajj and Umrah seasons where millions of passengers land on the Kingdom's airports within a short period of time. The four Saudi airports during the 2025 Umrah season managed to serve over 6.8 million pilgrims (Saudi Gazette, 2025). The seasonal nature of traffic at these airports results in a huge increase in discarded tire rubber on the runways and a tremendous challenge for maintenance personnel to remove the rubber from the pavement. Due to the operational need to keep as many hours on the runways open as possible during these surge periods, there are very narrow windows to remove the discarded tire rubber and to perform other required maintenance activities.

In addition to the normal traffic stress to which pavements are subjected in Saudi Arabia, the extreme climate affects pavement management. High ambient temperature, high pavement surface temperature, intense UV radiation and high diurnal temperature fluctuation accelerate oxidation of asphalt binder, hardening of asphalt binder and promote thermal cracking. The flexible pavement surface temperature in Saudi Arabia can range from 3° C to 72° C. This in turn produces large thermal gradients through the surface layer, which increases fatigue and further cracking and delamination. Additionally, traffic stress, and degradation and accumulation of rubber from vehicles must be managed to achieve optimal pavement life.

The study airport is one of the international airports in the western region of Saudi Arabia, and it is expected to handle more than 10 million passengers by 2024. This airport has one of the main entry points for Umrah pilgrims, in addition to regular air traffic movements which result in heavy seasonal traffic plus heavy year round traffic. Both seasonal and year round traffic will be constrained to one pavement structure, the single main runway designated as X/Y. This single runway is expected to support all air traffic movements at the airport, and will be subject to a variety of different commercial aircraft, ranging from the narrow body, regional jet aircraft to the wide body, long haul commercial aircraft now in service. The asphalt concrete pavement surface will undergo degradation due to a variety of mechanisms or modes, including simultaneous and interactive degradation from rubber contamination, traffic polishing,

thermal degradation, oxidation hardening, and maintenance activities. The study airport pavement provides a unique scenario in which to study pavement degradation under one of the world's most demanding environmental conditions.

Friction management at aerodromes is a significant business that affects safety and overall aerodrome operations. Currently, friction on the runway is checked periodically using Continuous Friction Measuring Equipment (CFME). Readings from CFME are compared against specific threshold values provided by ICAO and locally implemented by General Authority of Civil Aviation (GACA). Many in the aviation industry and aviation governing bodies around the world are moving from this reactive approach to an optimised friction management strategy. The runway friction management strategy in place at an airport would be an optimised system that takes in to account many parameters affecting the friction on the runway and incorporates them in a decision support system. The need for such a system led to this research study.

1.2 Problem Statement

Runway maintenance practices currently employed within the commercial aviation sector, including airports within Saudi Arabia, follow a largely reactive approach in relation to managing friction on wet runways. Friction is currently measured and debris removed on a regular or event triggered basis. This typically occurs when the measured friction is reported to be below a declared Maintenance Planning Level (MPL) or during critical weather periods at readings below the Minimum Friction Level (MFL). The current approach fails to adequately consider all pertinent variables in assessing friction levels and treats each reading in isolation rather than as part of a trend. Consequently, the risk exists that maintenance intervention will either occur too late, potentially endangering lives as well as causing significant aircraft ground damage, or too early thereby removing remaining life from critical airport pavement structures.

The reactive paradigm has many limitations. In management of pavement friction on runway surfaces, the threshold system outlined in ICAO Doc 9137 is followed by all airport regulatory bodies including GACA in Saudi Arabia when establishing MRCs in Airport Operation Manuals. This threshold approach to pavement friction does not take into account a number of important factors, for example, trend, path of degradation, and remaining life. For example, in a reactive paradigm a runway with a friction reading of

0.53 is considered to be operationally safe by regulators and Aircraft Operators at the same time if only marginally above the threshold of 0.52 MPL under ICAO standards. In a similar manner, a runway decreasing gradually in friction at a rate of 0.03 per month due to heavy usage with excessive loading is viewed as a more serious condition than a similar runway at 0.53 which remains at that stable level of friction over the past six months of light usage. A critical gap in the reactive paradigm that currently governs management of pavement friction on runway surfaces needs to be addressed in order to support better proactive runway friction management and overall airport safety. Reactive maintenance does not provide protection from critical friction deterioration. Reactive maintenance is typically planned and executed at the worst possible time to place safety margins at risk. Additionally, there is always a window of time between friction tests when the unknown friction condition of the runway poses the greatest risk to aircraft safety; yet this risk is more probable as traffic volumes increase. The faster friction is decreasing to unacceptable levels, the greater the consequences to both aircraft and operators should the unknown friction condition not be detected.

Secondly, the currently implemented reactive pavement friction testing approaches do not account for differences between airports, seasons, or operational directions with respect to the relationship between traffic intensity and friction degradation rate. Saudi airports experience huge seasonal variations in traffic volumes, for example during the Hajj and Umrah seasons when millions of pilgrims arrive to and depart from Saudi Arabia. A fixed-interval pavement friction testing approach developed using average traffic data from Saudi airports would not be able to adequately address the friction performance needs on the high-traffic volume days (such as those experienced during peak season) but could result in excessive testing on low-traffic volume days (such as those experienced during the off season). The lack of a traffic responsive approach to conducting pavement friction tests results in a poor match between the rate of friction degradation and the test frequency. Three deficiencies in current practice have been identified regarding removal of rubber from Saudi aerodrome surfaces. The first deficiency is that most of the rubber removal is conducted on an emergency basis following a stopping incident. In many cases, the stopping incident could have been prevented if the friction surface were of an adequate level. The second deficiency is that the typical method for removing rubber from Runway is using the high-pressure waterjet which may damage the pavement surface while removing the rubber deposits and debris. The third and most important deficiency is that each removal of rubber from

the pavement surface removes material from the surface and induces further degradation. This in turn reduces the friction in subsequent braking incidents. The efforts required to recover adequate friction in subsequent braking incidents will become less effective and the overall effort to achieve safe braking on the aerodrome surface will deteriorate to the point of significant loss of friction and braking safety.

Observations of decreasing returns from an Aerodrome pavement maintenance program are presented using operational data from Runway X/Y. Season after season, the post-removal friction recovery has decreased each year after each maintenance cycle, removing increasing amounts of friction capacity from the pavement. This decreasing cycle of degradation requires a more sophisticated decision-support system to guide operational maintenance decisions as opposed to reactive, threshold-based approaches. The cycle of degradation is created in part by the maintenance program itself. Traffic deposits rubber on the surface, followed by declining pavement friction, aggressive cleaning to restore friction, and damage to the pavement during the removal of rubber from the surface. The pavement then collects rubber at an increased rate, followed by further declining friction that is addressed through more frequent aggressive rubber removal from the pavement surface. Understanding these processes and how they create the cycle of degradation allows airport managers to break the cycle before significant irreversible losses in friction capacity occur, avoiding premature full-depth reconstruction and saving millions of dollars.

There is no established foundation within airports for linking together air traffic characteristics, friction measurement trends, methods for removing deposits of rubber from runways, and methods for assessing pavement. In the current literature, each of these issues is considered separately. For example, standards for friction measurement do not take into account traffic characteristics, methods for removing rubber from airport pavements do not take into account long-term implications for pavement maintenance, and pavement management systems primarily do not use friction trend information as an input parameter. Traffic parameters monitored for air traffic management purposes are not used as input for pavement management. As a result, airport operators are unable to make well-informed, multi-disciplinary decisions regarding the trade-offs between short-term safety needs and long-term pavement preservation needs, while striving to achieve cost-effective solutions over the life of the pavement.

The adequate management of pavement friction levels is one of the challenges facing airport management to ensure safe aircraft operations. The Saudi airports face this challenge due to the large operational traffic during the major pilgrimage seasons, unpredictable weather, rapid air pavement deterioration, and large air traffic volumes to meet Saudi Vision 2030 growth targets. Inadequate friction levels pose various risks such as safety occurrence, operational disruptions (emergency maintenance on the runway), regulatory compliance risks (reduced airport capacity due to NOTAMs issued for slippery runways), inefficiency, and poor services to millions of pilgrims and international air travelers traversing through Saudi airports. However, proactive and systematic friction management enables airfield pavement managers to develop a maintenance schedule, time operations and methods correctly, and remove rubber from pavement surfaces effectively to achieve safety and economic gains. This research presents a decision-support model for airports' friction management utilizing various data collected from a Saudi airport study site.

1.3 Research Objectives

The objectives of the study are to investigate the relationships between air traffic parameters, runway friction, runway rubber removal methods and pavement deterioration. A decision-support methodology and its application are developed to aid maintenance decisions to optimise the utilisation of Saudi aerodrome runways as follows:

Objective 1: The overall objective of this three-year research project is to develop the capability to predict runway condition. To achieve this first objective, we will investigate the relationship between flight-traffic parameters (e.g., landing frequency, weight categories, seasonal variations, end usage) and measured CFME runway friction levels. In turn, we will develop equations that describe friction loss or degradation in terms of accumulated traffic.

Objective 2: Assess various methods for rubber removal from freestanding rubber and their effects on the pavement surface structure. Identify cumulative effects on surface texture, binder, friction, and recovery between events and then develop a compounding degradation cycle that describes how repeated instances of aggressive maintenance affect long-term pavement degradation.

Objective 3: Comparison of effectiveness, cost, pavement preservation and safety of reactive (as current practice) versus predictive (new approach) maintenance strategies for RWY friction management. Historical data from the study airport will be analyzed to quantify differences in cycle frequency, pavement life cycle and other operational parameters.

Objective 4: Development of practical decision-support system that integrates information traffic, friction data, pavement and maintenance data, enabling airport management at Saudi aerodromes and other airports worldwide to make optimal decisions.

1.4 Research Questions

To accomplish the goals of this study, the following research questions will be addressed.

RQ1: How do variations in runway maintenance practices and the outcomes thereof (asphalt temperature exposure, compaction, water application rates) (a) account for between-runway variability in friction degradation rates and (b) interact with other air traffic relevant parameters to create friction deterioration dynamics over time and space.

RQ2: How do rubber removal frequency and technique parameters can the extent of pavement surface condition degradation and characteristic longitudinal friction profiles?

RQ3: Over a multi-year planning horizon, compare safety, maintenance frequency, pavement preservation and LCC for reactive versus predictive maintenance approaches. This includes friction margin above MFL, number of rubber removal events, rate of baseline friction decline, and friction loss over time.

RQ4: Development of an integrated decision-support framework, and related methodologies, to support aerodrome operators to make rational decisions regarding the timing of proactive (i.e. preventive) runway maintenance, based on Traffic, Friction, Pavement Condition and Maintenance planning algorithms data, and a shift from reactive to predictive strategies.

1.5 Research Hypotheses

Based on the research objectives and questions, the following hypotheses are proposed:

H1: There is a significant relationship between air traffic intensity and the rate of runway friction deterioration.

H2: Frequent rubber removal operations increase the pavement surface deterioration and reduce the after-maintenance friction recovery over time.

H3: Predictive maintenance strategies improve cost efficiency and extend pavement service life compared with reactive maintenance strategies.

H4: An integrated decision-support framework improves runway maintenance planning effectiveness compared with traditional reactive practices.

1.6 Significance of the Study

This research contributes both to the academic operational management research and to the practical day-to-day needs of stakeholders in the aviation system.

1.6.1 Operational Safety Significance

For safe aircraft operation, adequate runway friction must be provided during both landing and takeoff phases of flight. Runway excursions, the most common type of accident globally (IATA 2025 Safety Report), can be caused by a variety of factors, including those related to wet runway conditions and poor braking performance on reduced friction surfaces. In the latest RWY EX report by the Flight Safety Foundation, 83% of all reported runway excursion accidents could have been avoided by simply performing a go around; however, subpar braking performance played a role in 59% of the accidents reported. This research develops a method for the detection of decreasing friction levels and corresponding scheduled maintenance to prevent subpar braking performance and associated safety risks before safety margins are compromised. The predictive capability of the developed framework will provide the operator sufficient warning of approaching friction threshold values to allow for scheduled maintenance before threshold values are compromised. Runway Excursion Events at high traffic volume pilgrimage airports in Saudi Arabia and around the world are a serious safety

issue. Given the times of the year at which these airports experience the highest volume of travelers, efforts to proactively manage risks related to reduced friction on airport surfaces have particularly high safety significance.

1.6.2 Engineering and Pavement Management Significance

This research studies the currently underappreciated connection between rubber removal practices and the long-term degradation of airport pavement with engineering significance throughout the pavement's lifecycle. Rubber removal success is typically measured post event by the new friction level; however, current practices also have the added consequence of short-term friction restoration and long-term pavement degradation. In this study, the effects of repeated removal cycles on the surface of the pavement and the rate of friction restoration between cycles are monitored and recorded. The resulting study not only provides engineers and practitioners with important insights regarding removal technologies, operational parameters such as water pressure and nozzle angle/distance, and the appropriate timing of intervention, but also reveals the compounding degradation cycle generated by increasingly aggressive and frequent maintenance strategies. The study's findings have important and timely implications for effective Pavement Preservation strategies for Airports globally. This type of analysis can be utilized to extend the lifespan of existing pavements and prevent costly early rehabilitation events that remove structures from service for months.

1.6.3 Financial Significance

Runway rubber removal presents significant challenges to airports. Although several removal technologies and strategies are available, most remove rubber from the pavement surface on a zone by zone basis, typically closing the runway for 8 to 12 hours per treatment zone. The cost to remove rubber from a single treatment zone can be from \$50,000 to \$200,000 or more per event. This is particularly significant when compared to the multiple millions of dollars required for major pavement reconstruction efforts that can take airport capacity out of service for extended periods. The ultimate goal of this research is to reduce both the direct cost of removal as well as the indirect cost associated with closing runways to aircraft operation. The result would be to establish a tool to help airport managers determine the best time to perform maintenance while contamination is light enough to remove using lower pressure technologies as

opposed to waiting for heavier contamination that requires more aggressive methods. This approach is called predictive maintenance of infrastructure assets, and numerous studies have shown a 15 to 30 % reduction in total lifecycle costs of maintenance using this approach compared to reactive maintenance strategies (de Solminihac et al., 2018). Apart from several technical benefits of the model, it is also expected to extend the service life of pavements reducing the maintenance induced damage. This approach may save huge initial investment required for resurfacing or reconstruction which the rapidly growing Saudi airports may not need for sometime to come. The real financial benefits of optimising the runway maintenance for Saudi airports could thus be huge releasing huge capital for increasing their capacity rather than premature reconstruction of pavements.

1.6.4 Regulatory Significance

The findings of this study can be useful to the General Authority of Civil Aviation (GACA) and other governing bodies to determine if a threshold-based approach to regulatory requirements could be augmented by a trend-based monitoring methodology for safety. The current structure of the regulatory environment as reflected in GACAR Part 139 (Airports – Visual Aid for the Certification/Deregistration of Airports) is based on the minimum requirements as outlined by ICAO Annex 14 and supported by Doc 9137. However, this regulatory environment does not presently outline the use of friction measurements for predictive, proactive, and proactive, maintenance strategies. The findings from this study can be useful in aiding the revision of GACAR Part 139 as well as other related guidelines and advisories. Specifically, the study illustrates the shift in the regulatory environment for airport operations from a purely prescriptive structure to one that is performance based for safety management. This shift is consistent with many aspects of the ICAO safety management system as defined by ICAO and in line with the policies of the General Authority of Civil Aviation. The findings indicate that today's airport operators need to move from a compliance based mindset related to surface friction measurements to a safety risk management mindset and strategy utilizing all available data. The study illustrates a methodology for supporting the friction management decisions for airport operators world-wide, including those in Saudi Arabia, and can serve as a prototype or model for future regulatory methods for managing friction on airport surfaces.

1.6.5 Academic Contribution

The research presents an integrated framework of five independent fields to support predictive and optimisation-based airport maintenance decision-making. The individual fields of friction measurement, rubber accumulation, pavement deterioration, traffic analysis and maintenance optimisation have all been studied in isolation within the existing literature. However, no previous research has integrated these related fields into a single model that can be validated and used for airport maintenance management. The study offers a unique contribution to the field of aerodrome engineering and opens the door for future research using large datasets of operational airport data. The research also undertakes a longitudinal study of the friction from multiple maintenance cycles at an operational Saudi airport. Published information on the friction of Middle Eastern airports is extremely limited. The study also offers a unique contribution to the pavement engineering field by identifying and documenting the compounding degradation cycle and its effects, which have applicability in non-airport situations where surface skid resistance is a consideration.

1.7 Scope and Limitations

The scope of the spatial assessment relates to the individual study airport identified in the western region of Saudi Arabia. The name of the airport, and its ICAO designated location, have not been included in the document to support objectivity of the findings.

The selected runway, designated as Runway X/Y, is the main Runway of the study airport. Therefore, it was considered the primary runway to assess friction and associated maintenance operations.

Temporal Scope: The data has been extracted from an operational environment and the time scope for this analysis is on the order of 3 years. Starting from 20th February 2023 and finishing on 31st January 2026. Alongside the cycle data, friction readings, maintenance records and traffic information have been collated to provide a comprehensive analysis.

Published friction test results from various sites are combined with air traffic data, tyre rubber removal data and pavement deterioration information and tested for correlations. The test vehicle was an ASFT certified vehicle.

The purpose of this study is to investigate the relationship between traffic, runway friction, and the removal of rubber from the pavement surface. This report does not address the structural design of the pavement, the drainage beneath the pavement or any other airfield related systems that are not friction related.

Data Collection Scope: 10 friction test reports taken at various locations around the airport from the CFME using a certified ASFT vehicle traveling at a constant speed of 65 km/h. The tire utilized for the tests was an ASTM rated tire with a 1.0 mm water film applied. Additionally, the study uses 28 months analysis of air traffic data, which included information on specific aircraft types, weight categories, direction of landing on each end of the runway, and frequency of landings for each specific approach. The study uses information, including specific maintenance actions, techniques, and results, pertaining to the airport's rubber removal program. The study uses and analyzed pavement condition information for all locations from various visual inspection reports.

The study focuses on a number of key themes. First, the study looks at traffic, and how traffic operations are managed on individual runways. Secondly, it explores the friction performance achieved under different conditions. Thirdly, effective rubber removal from the pavement is studied, and finally, the current state of the pavement (runway) as it relates to good runway surface management is examined. The study does not address other related but separate issues such as structural pavement design, subsurface drainage, airfield lighting and marking maintenance, and airside safety management. A quantitative documentary analytical approach is used, the study does not include any surveys or interviews as part of the methodology.

Acknowledged Limitations:

The study has several acknowledged limitations:

1. The study data is based on a single aerodrome therefore while information concerning the amount of reduction in friction developed will be quantified, subsequent application to other airports will be influenced by a number of factors including pavement type, aggregate characteristics, operating conditions and traffic configurations.

2. Friction values obtained from different types of friction measuring equipment (CFME) are specific for the type of friction measuring equipment (CFME types) used here, i.e. Airport Surface Friction Tester (ASFT) specific and NOT general. Values obtained from other friction measuring equipment (e.g. Mu-Meter, Grip Tester) will not match without use of specific correlation factors.
3. Environmental variability: Variables such as temperature and humidity at the time of the test are recorded, but uncontrolled in the actual testing. This variability in test conditions must be accounted for when assessing variability in emerging trends.
4. There are some gaps in the data for certain periods during the study time frame. These mainly relate to transition / change over of administration / systems at the airport and have been recorded and the potential impact considered.
5. Predictive modeling limitations: The predictive modeling component of the simulator program is based on the historical trends for various machine operations. This type of prediction is suitable for operational forecasting for short to intermediate periods. The historical trend extrapolation method used does introduce uncertainty in the numerical values of the forecast quantities, particularly for longer periods. A friction model that is based on a more mechanistic approach would offer greater accuracy for long term forecasts.
6. Pavement condition assessment - The pavement condition data were extracted from visual inspection reports and used to slightly assess the deterioration of the pavement.

1.8 Definitions of Key Terms

The following table defines key technical terms which are used in this study, providing standardized definitions to be sure that clarity and consistency of interpretation are in place.

Term	Definition
Friction Coefficient (μ)	The friction coefficient is defined as a dimensionless value describing frictional force at the tire–pavement interface as a ratio of normal force. Friction coefficients determined with the CFME are restricted to the range of 0 (zero friction) to 1.0 (very high friction). Typical friction coefficients for runway surfaces range from 0.40 to 0.90.
Continuous Friction Measuring Equipment (CFME)	Friction testers are specialized equipment that carry test tires and a water supply and travel down the center of a runway at a constant speed. They record friction data during travel and generate friction profiles for every section of the runway.
Airport Surface Friction Tester (ASFT)	A specific version of the commercial friction measuring equipment (CFME), a major European OEM model. It operates at 65 km/h with a fixed-slip test wheel and an ASTM standard test tyre. This is the specific type of CFME used in the study reported in this paper.
Design Objective Level (DOL)	A measure of the friction that will be experienced on a newly constructed or resurfaced runway. Typical friction values for ASFT at 65 km/h are around 0.72 and are used to evaluate pavement construction quality.

Maintenance Planning Level (MPL)	Maintenance Planning Level (MPL) is the threshold below which maintenance must be planned. For the ASFT condition of 65 km/h this parameter has been set to 0.52.
Minimum Friction Level (MFL)	The minimum friction value where immediate action is required, and a NOTAM needs to be published. This parameter defines the absolute lower limit of operational safety. For the ASFT condition of 65 km/h this parameter has been set to 0.42.
Macrotexture	The macro texture of pavement is in the frequency band between the aggregate size and 50 mm (wavelength of 0.5–50 mm), which is the major roughness forming a large-scale undulation on pavement surface. The function of macro texture is to enhance water drainage from the contact area between tire and pavement surface and to resist the danger of hydroplaning at high speeds. The mean texture depth (MTD) is often used to measure the macro texture.
Microtexture	The fine-scale surface texture of individual aggregate particles (wavelength < 0.5 mm). This texture is primarily responsible for direct tire–pavement contact and adhesive friction at lower speeds. The characteristics of microtexture are largely determined by

	the mineralogy of the aggregate and its polishing resistance.
Rubber Accumulation	The progressive build-up and deterioration of the vulcanized rubber from tires leaves a build-up on the surface, predominantly in the touchdown zone during aircraft landings. The rubber fill-in of the micro- and macrotexture reduces friction.
Rubber Removal	Removal of the rubber accumulated on pavement surface, using methods such as high-pressure water, chemical treatment, shot blasting and/or sweep cleaning to restore friction.
High-Pressure Water Blasting	The typical removal method involves blasting water at pressures ranging from 10,000 to 40,000 psi through rotary nozzles to remove the rubber from the pavement surface.
Touchdown Zone (TDZ)	The portion of runway distance AFTER the threshold, where the aircraft first touches down during landing. This area typically extends 300-900 meters from the end of the runway and typically shows the highest accumulation of rubber deposits.
Runway Portion A/B/C	The runway divided into three equal-size sections. These were designated as

	Portion A, which is the first third of the length of the runway from the threshold; Portion B, or the middle third of the runway; and Portion C, or the last third of the runway.
Compounding Degradation Cycle	The positive feedback loop identified in this study whereby rubber accumulation → friction decreases → aggressive rubber removal → pavement damage → faster rubber accumulation → accelerating friction decline, creating a self-increasing deterioration cycle.
NOTAM (Notice to Airmen)	a NOTAM (Notice to Airmen) is a notice containing information concerning the establishment, condition, or change of any aeronautical facility, service, procedure, or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.
GACA	General Authority of Civil Aviation (GACA). The regulatory body for Civil Aviation in the Kingdom of Saudi Arabia.
GACAR	The General Authority of Civil Aviation Regulations (GACAR) are a set of rules and minimum operating standards that must be met in order to conduct civil aviation operations in Saudi Arabia. These Part 139 regulations cover the

	certification and operation of airports and ground facilities (the aerodrome) that receive scheduled commercial air service.
ICAO	The International Civil Aviation Organization (ICAO) is a specialized agency established by the United Nations to develop and establish international standards for aviation under agreed Schemes of Certification. The standards, technical provisions and recommended practices developed by ICAO are known as Standards and Recommended Practices (SARPs).
PCR/PCN	Pavement Classification Rating/Number: (ACRP) A numerical classification rating which indicates pavement strength relative to the loads imposed by aircraft on the pavement.
Predictive Maintenance	Maintenance approach uses data analysis, trend monitoring and forecasting to ensure maintenance is performed before components reach critical threshold levels, thus eliminating the need for reactive maintenance and instead executing maintenance on a proactive basis.
Reactive Maintenance	Corrective maintenance is a reactive strategy where equipment, machinery, or

	software is repaired or replaced after a failure or fault has occurred
Decision Support System (DSS)	Operational information systems for decision support, combining internal and external data and using analytical models to generate decision alternatives.
Vision 2030	Saudi Arabia unveiled a national strategic plan in 2016 to drive economic diversification, and the country's aviation sector will need to process 330 million passengers per year, triple current levels, to meet its long-term objectives.

1.9 Organization of the Study

This document consists of two chapters that introduce the reader to the theoretical framework that governs this research study as follows:

Chapter 1 introduces the reader to the background of the study, problems under investigation, objectives of the study, research questions and hypotheses, significance of the study, scope of the study and terms and definitions that are used in the study.

Chapter 2 reviews existing literature on topics such as runway friction, tire rubber on pavement, pavement deterioration and maintenance practices. In addition, literature on decision support systems related to the aforementioned topics is presented. These two chapters will form the basis of the empirical and analytical approaches taken in the rest of the study.

Chapter 2 LITERATURE REVIEW

This chapter collates existing knowledge relating to runway friction management, the issues of accumulating rubber on the surface, potential damage to pavements, routine maintenance operations and the decision support tools which currently exist. The chapter serves as a foundation to the rest of this thesis and highlights the specific area of research that the integrated framework addresses.

2.1 Introduction to the Literature

This chapter reviews and assesses available research and practices in the following areas: 1) friction management of runways; 2) rubber contamination of pavements; 3) pavement management, assessment, and design; and 4) cost-effective on-time and efficient maintenance practices. The chapter lays the groundwork for the current study by reviewing relevant knowledge. The review also identifies research and practices gaps this study will attempt to address. Specifically, the review has identified a need for an integrated model that forecasts friction, traffic, rubber removal effects, and pavement performance to support maintenance decision making.

The review is organized into sections of similar length corresponding to the logical sequence of the research problem as defined initially. These sections cover: 1) Basic concepts of friction science; 2) Friction measurement methods; 3) Pavement degradation mechanisms due to traffic; 4) Laws and regulations; 5) Mechanisms of pavement surface contamination; 6) Friction reduction mitigation measures; 7) Unintended consequences of friction restoration; 8) Traffic as the main degradation factor; 9) Maintenance decision making. A knowledge gap has been identified concerning the complete integration of the above aspects.

The literature review for this research has been conducted across a variety of disciplines including general pavement engineering, airport management, aviation laws and regulations, tribology and asset management. A number of primary sources have been reviewed, which include regulatory documents and guidelines developed by ICAO, the FAA, GACA and the UK CAA. In addition, numerous secondary sources of both peer reviewed research papers (Transportation Research Record, International Journal of Pavement Engineering, Tribology International, Journal of Transportation Engineering

etc.) and technical reports published by the Transportation Research Board (TRB) and other organizations around the world have been consulted. Finally, a number of classic texts on general pavement engineering and airport design have been consulted as they remain key sources of information on these topics regardless of publication date.

2.2 Runway Friction Fundamentals

Runway friction is a complex interaction of physical laws that occur between an aircraft tire and the pavement surface, affected by all contaminants to the surface including water, rubber deposits, ice and other substances that may be present on the surface. Understanding the generation and degradation of friction as it occurs between an aircraft tire and pavement surface is crucial to understanding why rubber contamination decreases friction, why some de-icing agents may only provide temporary and limited friction recovery, and why an integrated approach to controlling contamination is essential to safe aircraft operations.

2.2.1 Microtexture and Its Role

The microtexture of the individual aggregate particles forms the fine-scale roughness which is known as the asperities or micro-asperities. Their characteristics are expressed in the two parameters: feature height (fh) and feature wavelength (fw). The feature wavelength should be limited to values below 0.5 mm. The fine-scale roughness of the stone surface creates microscopic asperities penetrating the thin film of water present during wet-weather conditions. This allows physical contact between tire rubber and stone surface, resulting in friction forces mainly due to adhesive forces (intermolecular forces at the interface) and hysteretic forces. The latter involves energy dissipation of the rubber during deformation over the surface of individual stones. Relevant during low speeds before braking, around 80 km/h or less.

The microtexture of an asphalt pavement surface is largely a function of the mineral composition and texture of the aggregate. Siliceous aggregates (for example granite, quartzite, sandstone) generally provide better microtexture than calcareous ones (for example limestone). However, some calcareous aggregates have been shown to provide good microtexture. There is general agreement that aggregates with a high Polished Stone Value (PSV) are less susceptible to polishing.

The microtexture of aggregates is decreased in two important ways. First, traffic effort produces polishing on the surface of individual aggregates, removing peaks which provide traction for water to cling to. This surface polish is also contaminated with rubber from tire cracks and crevices. The rubber film which coats the individual stone has very little wet friction with the tire. Traffic polishing is a function of the logarithm of the number of passes and is highest in the first few years of service life. After that, the polishing rate decreases and can reach a constant rate depending on the physical properties of the individual aggregate. In a recent laboratory study by Bobrovnikov et al. (2025) deposited rubber was shown to decrease friction by deposited rubber masking pavement microtexture. The study showed the effects of deposited rubber on tire–pavement interaction. This study investigates the effects of deposited rubber and removal of deposited rubber to reverse the decreases in friction and to achieve improved friction (Noyce et al., 2005).

2.2.2 Macrottexture and Drainage

Macrottexture is concerned with the surface texture of pavement over a wavelength of 0.5 to 50 mm. In particular, it is concerned with the overall surface roughness and the extent of the space between individual aggregate stones, as well as the surface profile. Whilst microtexture provides skid resistance through physical contact, macrottexture provides sufficient drainage area as speed increases to enable water to escape laterally above the tyre contact patch. If the pavement surface does not possess sufficient macrottexture, the area of the contact patch is soon filled with water leading to either partial or complete hydroplaning. In these circumstances, the tyre is either only partially in contact with the pavement surface, or completely separated by a film of water with little or no friction between the two (Henry, 2000).

The contribution of macrottexture to friction becomes increasingly important as speed increases above 80 km/h. For aircraft, the “touch down” speed for the landing distance calculation is greater than 250 km/h, but reverse inspection friction measurements using the ASFT are conducted at a constant speed of 65 km/h, at which time both microtexture and macrottexture are contributing to the measured friction. The International Friction Index (IFI) developed by the Permanent International Association of Congresses (PIARC) models friction as a function of speed with a macrottexture- dependent speed

constant. This constant is a function of texture depth and friction at several speeds (Wambold et al., 1995).

The parameter of macrotexture can be presented in terms of Mean Texture Depth (MTD) that can be determined either by sand patch method (ASTM E965) and measure MTD in terms of distance in millimeters, or by laser profilometry to determine Mean Profile Depth (MPD). ICAO Doc 9137 recommends an average MTD of not less than 1.0 mm for new runway surfaces to provide effective drainage. The studies conducted by Kouchaki et al. (2018) on the relationship between pavement texture and friction showed positive correlation between macrotexture and friction performance at different test speeds. The studies also highlighted the role of macrotexture in providing wet friction.

Deposits of rubber stick to surfaces reducing the macrotexture as the inter-aggregate voids and surface drainage channels become filled with the adhering deposits. The result is a decrease in texture depth which in turn decreases the ability to drain water. The effective thickness of the water film under the tyre increases, leading to a decrease in friction. For a rubber contaminated runway, the effect on friction is marked with a very large reduction in friction when wet as compared with the dry conditions. In a recent study by Zhu et al. (2021), the effects of deterioration of runway surface texture on friction were investigated, confirming that worn surfaces in wet weather are a major contributor to reduced skid resistance resulting in increased risk of poor control during the landing roll. Furthermore, the speed to hydroplaning is greatly reduced.

2.2.3 The Two-Level Texture Model

The two-level texture model illustrates the relationship between microtexture and macrotexture and friction. The model has been used to assess the relative impacts of different surface deterioration processes on friction. It states that at speeds below 60 km/h, friction is primarily affected by the model's first level and the tire's ability to make contact with the pavement through the water film as the surface's microtexture dictates good or poor friction performance. At speeds above 80 km/h, friction is affected by the pavement's ability to drain water, as the tire must make contact with the pavement at all and the pavement's macrotexture must be sufficient. At intermediate

speeds, both micro- and macrotexture must be adequate to maintain good friction performance.

When evaluating the texture of a pavement surface, it is typical to divide the texture characteristics into two main categories - micro texture and macro texture. In friction management, the model suggests that the way rubber contaminates the pavement surface, through coating, decreases the micro texture and macro texture differently. While the removal of rubber from the pavement surface can return both the micro and macro texture to satisfactory levels, the extent to which the surface texture is restored depends on the condition of the underlying pavement structure. For example, if individual aggregate particles have been polished to a smooth surface, or if they have become loose from previous removal cycles, removal of the rubber will not increase the macro texture component. Furthermore, the post-removal friction levels are likely to be below the Design Objective Level.

In their study Kováč et al. (2023) explored the influence of road pavement materials on surface texture characteristics and their relation to pavement friction. Their results show that a high level of macrotexture does not necessarily translate into high friction values and that a high quality of microtexture is also required. These findings support the previously introduced principle for road surface friction management from a multi-parameter perspective.

2.2.4 CFME Measurement Principles

This test device continuously measures friction. The friction is measured between a test tire and pavement surface. The device is an ASFT (Automated Speed Friction Tester) as well as the Mu-Meter and Grip Tester. The certified ASFT vehicle shown here is traveling at 65 km/h. A uniform film of water is generated ahead of the test tire. The test tire can be set in a fixed-slip configuration or a side-force configuration. The certified ASFT vehicle shown is operating with a fixed-slip configuration. The ASTM standard test tire is traveling at a slip speed which is slightly less than the vehicle travel speed and therefore is slipping at a specific slip speed.

The friction coefficient is calculated as friction force divided by tire load. Friction values are collected at a high sampling rate (approximately 1-2 meters) and then

reported as a rolling average over the specified sampling interval. In the ICAOPG (ICAO) report, the friction values for each portion (A, B, and C) of the runway are reported as an average of the values collected along each portion, with each portion being 1/3 of the total length of the runway. In addition to the averages for each portion, 100-meter rolling averages are provided to aid in identifying any deficiencies in friction over a 100-meter section within a portion. The minimum of these 100-meter rolling averages is compared against the Maintenance Planning Level (MPL) and the Minimum Friction Level (MFL) to determine if maintenance is required. (ICAO, 2020).

Reliability and reproducibility of CFME measurements are important for effective CFME-based trend analysis and timely maintenance decision making. Even though Mataei et al. (2016) reported that CFMEs are reliable under well-controlled test environments, there are other factors, such as ambient temperature, tire characteristics, water film uniformity, and vehicle speed control method, which can affect the reproducibility of CFME measurements. For the ASFT vehicle, it is anticipated that the measurements will have a repeatability of 2-5% (coefficient of variation) under constant test conditions. This level of repeatability is adequate for assessing current friction levels but not sufficient to detect small changes between data collections for purposes of trend analysis. Baimukhametov and White (2024).

2.2.5 Factors Affecting Friction Readings

While the classical texture-friction relationship holds, several other operational and environmental parameters may also influence the values of CFME.

Temperature effects: Ambient temperature and pavement surface temperature affect both tire rubber and asphalt binder. Tire rubber becomes softer, more compliant with surface texture, and therefore measures higher friction as temperature increases. Asphalt binder becomes softer as temperature increases, which can cause aggregate particles in surface course to become unstably agitated. Field studies have documented that friction measurements taken at the same location on the same road surface can vary by 0.02 to 0.05 between hot and cool field conditions (Flintsch & McGhee, 2009).

Friction is speed dependent, and as test speed increases, friction generally decreases due to increased hydrodynamic effects. The 65 km/h test speed for the ASFT is a

compromise between using the ASFT as a microtexture test (which should be conducted at lower speeds) and as a macrotexture test. Measurements made at different test speeds should not be compared without application of correction factors. These correction factors have been determined and are included in the IFI harmonization model. (Wambold et al., 1995).

Water film thickness: The pre-specified water film thickness (1.0 mm for ASFT testing) affects measured friction positively, meaning higher water film thickness leads to lower friction due to increased hydrodynamic separation. Too low a water film thickness may not provide the runway conditions for wet pavement simulation required for the test. Achieving consistent water film thickness is critical for this test.

Friction – Tire condition: The test tire conditions such as new, worn, hard or soft can affect the friction coefficient levels measured. ICAO, tire manufacturers and other guidelines can be used to determine when to replace the test tire. Between replacements, tire wear occurs at a relatively predictable rate, which results in a slow drift in the long-term trends.

Seasonal and diurnal variations: runway surface friction measurements can be affected by time of day (temperature) and by season (condition of pavement surface etc.). In the study area Saudi Arabia, the runway surface friction can be affected significantly by the difference between summer and winter pavement surface temperatures, as much as nearly 70°C. Hence, normalizing the data by season is an essential step to identify meaningful trends.

2.3 Rubber Accumulation Mechanisms

During flight operations at airports, the tire rubber from landing aircraft is inevitably deposited on the runway surface. An understanding of the underlying physics is required to predict locations of rubber accumulation, rates of accumulation and effects on friction.

The main landing gear tyres of an aircraft experience a "spin-up" during landing, where the ground speed changes rapidly from zero to the operating landing speed of 130-160 knots (24-30 m/s), which corresponds to the taxiing speed on ground. A skidding

condition occurs at the tyre-pavement interface where the high-rate-of-change-of-velocity results in extremely high frictional heat leading to high surface tyre temperatures that can reach 250°C or more. The outermost tyre layer gets molten and adheres to the pavement surface to form a ground bond. Studies have shown that the ground bond is a polymerised, chemically cross-linked polymer that adheres to the pavement surface texture. The polymer layer is difficult to remove and, as it ages, it gets progressively compressed into the pavement porous structure during subsequent landings and ground movement.

The majority of tire rubber deposition occurs in the touchdown zone of the runway, typically the first 600-900 meters from the touchdown zone threshold. Research has demonstrated that there are approximately 500-700 grams of tire rubber deposited per commercial aircraft landing on the surface of the pavement. This parameter is affected by several factors including aircraft weight, tire pressure, landing speed and crosswind. In general, rubber deposition is greater from wide-body aircraft incorporating multi-wheel main landing gear assemblies than from narrow-body aircraft. Estimates indicate a heavy aircraft landing could deposit up to 10 kg of rubber on a new pavement surface; however, such estimates are likely excessive.

The pattern of contamination left on the runway surface by rubber from tires follows a predictable form. Initially, the rubber is deposited in a fairly uniform band of width approximately 6 to 8 feet wide and symmetrical about the runway centerline. The width of this band corresponds to the width of the main landing gear tracks of the particular type of aircraft that operate on the runway. Accordingly, measurements of rubber contamination made by a continuous friction measuring equipment (CFME) at 3-meter, 6-meter and 9-meter offsets from the runway centerline will each yield a different rubber contamination intensity. The intensity at the 3-meter offset will be greater for narrower runways that service smaller business-jet type aircraft and less for wider runways that service larger aircraft.

The distribution of rubber along the runway length follows the distribution of the touchdown point. Therefore, runway friction decay due to rubber deposits on pavement during operations De Luca, G., De Nardi, L., Pirozzoli, F., Saevarsson, F. *Journal of Air Transport Management*. 2016, 54. P. 69–75.

The distribution of rubber, for example, has the highest density between 300 and 600 m from the threshold for normal ICFs, decreasing smoothly to zero at the centreline. Although thousands of landings are required to produce significant contamination, the deposit is not sudden but continuous, decreasing smoothly towards the centreline. The longitudinal friction profile of a contaminated runway therefore develops a “valley” of low friction in the touchdown zone, which deepens with traffic as the last rubber removal occurs.

The rate at which tyre rubber builds up depends on many factors.

As landing frequency increases, traffic intensity increases and so does the rate at which tyres deposit rubber on the pavement surface, as well as the number of operational cycles required to remove it. In the paper by De Luca et al. (2016) an attempt has been made to model the friction decay as a function of the cumulative traffic loading. The results show that, for the initial stages of tyre rubber accumulation on pavement surface, friction degradation follows a near linear trend and tends to reach a plateau as pavement surface approaches saturation.

Aircraft Fleet Mix: Larger aircraft types, such as wide-body jets, generate more rubber per flight than smaller single-aisle jets. The ICAO aircraft weights are organized in five categories: five different weight categories from light (Category A) to heavy wide-body (Category F). The weight of one Category E/F jet is equivalent to the weight of several Category C jets, thus one single landing of an E or F jet can potentially generate as much rubber as several C jet landings.

Spin-Up: Environmental, Higher ambient temperature has a small negative effect on the rubber deposition as the more elastic rubber is less likely to crack and shed than at lower temperatures. Inflight, Lower ambient temperature causes an increase in skid which in turn causes an increase in rubber transfer. Spin-Up, The crosswind affects the lateral distribution of the deposits during the landing roll as the landing gear are crabbed to the runway centerline.

New: Easily removable because freshly deposited rubber is soft. Aging: Because UV light, traffic compaction, and thermal cycling harden, over polymerize and seal the

rubber to the pavement, removing old rubber is very destructive and can cause more damage to pavement than new rubber.

Sales, et al. (2021) – This paper evaluates the use of both pre- and post-slip tests for assessing tire–asphalt pavement adherence following the removal of rubber from two different removal procedures applied to tire debris from three airports in Brazil, using different pavement types. All of the removal methods evaluated presented effective results for ensuring minimum friction levels, but the benefits of the procedures studied did not translate to friction increases of more than 50%. The results partially confirm the partially restorative theory of the process and indicate that efforts should be focused on optimizing removal timing rather than removing 100% of the rubber.

2.4 International Friction Standards

The currently prevailing regulatory framework for dealing with friction on runway surfaces is top-down driven by a multi-level structure consisting of International Standards, National Regulations and Guidelines or Recommendations. This is due to the crucial safety aspect and the need for Global Standards that allow for different operationally relevant solutions in foreign countries.

2.4.1 ICAO Standards (Annex 14, Doc 9137)

According to ICAO Annex 14, Volume I, Chapter 10, Aerodrome operators must ensure that the runway surface, during its operating lifetime, has a surface friction sufficient to support safe Aircraft operations. The CFME and friction surveys of Aerodrome runway surfaces must be carried out periodically and, depending on the level of air traffic activity, appropriate action taken as soon as possible. The Aerodrome operator must notify appropriate personnel and other stakeholders by issuing a NOTAM to indicate that the available runway may be slippery when wet.

ICAO Doc 9137, Airport Services Manual Part 2 (Pavement Surface Conditions), is a technical manual which details procedures for assessing pavement surface conditions to comply with requirements set out in Annex 14. The manual covers the technical specifications for Chain-Free Mean Exterior Field (CFME) Measurement Equipment,

test protocols for pavements, data reporting and threshold values for pavement friction. The ASFT threshold values for the test speed of 65 km/h using an ASTM tire are specified as three global threshold levels for friction management.

- Design Objective Level (DOL): 0.72 for new or resurfaced pavements.
- Maintenance Planning Level (MPL): 0.52. This is the trigger for planning maintenance activities.
- Minimum Friction Level (MFL): 0.42 - The threshold below which immediate action must be taken.

CFME measurements must be conducted with self-wetting enabled and a calibrated water film applied (1.0 mm for ASFT). The average surface texture depth of the new surface must be not less than 1.0 mm (ICAO, 2015). For friction measurements, it is recommended that an average reading be provided for each runway portion (A, B, C) and a minimum 100-meter rolling average to highlight localized deficiencies.

2.4.2 FAA Standards (AC 150/5320-12)

Runway friction is addressed in The United States Federal Aviation Administration's Advisory Circular AC 150/5320-12C: Miscellaneous Technical Implications: Aircraft Taxiing: Surface Friction: Measurement, Construction, and Maintenance of Skid-Resistant Airport Pavement Surfaces. The FAA provides practical guidance to the measurement, construction, and maintenance of the roughness and friction of airport pavement surfaces. The FAA also outlines a traffic-based methodology for establishing a testing schedule for friction. The fixed-interval of five years between tests is addressed; however, this period of time can be reduced for high traffic airports (i.e. greater than 60,000 annual events). This partial address of the limitation is then critiqued.

Table 3-1 of AC 150/5320-12C recommends the following testing frequency based on annual jet operations: Less than 50,000 turbojet operations—semiannual; 50,000 to 200,000 operations—quarterly; More than 200,000 operations—test frequency will be established by the airport operator and the FAA, based on friction degradation rates for different traffic intensity levels.

Friction monitoring can be a valuable addition to an airport pavement management program. For information on incorporating friction monitoring into your airport pavement management program, please refer to the FAA AC 150/5320-6F Airports Engineering Notes for Airport Pavement Design-Part Six: Pavement Evaluation. This document provides guidance for airport pavement design, including structural design and selection of construction materials, as well as evaluation of existing pavement structures. The document addresses the related topics of pavement surface friction and overall pavement management to help airport managers make informed decisions to maintain and maximize the life of airport pavement assets (FAA, 2020).

2.4.3 GACA Regulations (GACAR Part 139)

Runway friction on active runways is regulated in Saudi Arabia by the General Authority of Civil Aviation of Saudi Arabia in the GACAR Part 139 (Certification, Authorization and Operation of Aerodromes) document. This is the rule book for the certification and operation of all civil aerodromes within the Kingdom of Saudi Arabia. Certified aerodromes must ensure that their runway surfaces are appropriate for safe aircraft operations, use an approved friction measuring device to measure friction on their active runways, record and manage the resulting data, and take corrective action when the measured friction is determined to be below the ICAO guidelines.

In a further step to strengthen aviation safety, aerodrome operators must now measure and manage airport surface friction as an important safety parameter and incorporate it into their safety management systems (SMS), and maintain relevant records to present to the GACA auditors. The GACA aerodrome regulations are based on the relevant ICAO Model Standards and also incorporate some local features related to weather like in Saudi Arabia, handling peak period traffic like during the Hajj and Umrah seasons, and the very rapid development of Saudi civil aviation infrastructure taking place under Saudi Vision 2030.

GACA has been gradually increasing its regulatory measures from traditional to more technological measures related to safety management and measurement based on data. Therefore, the study attempts to introduce a predictive methodology to schedule maintenance, based on historical data and other relevant variables. National Aviation Strategy aims to achieve the objectives of Vision 2030 in terms of transporting 330

million passengers through airports in the Kingdom to more than 250 destinations around the world. Thus, airports' regulatory policies and rules have to cope with current pressures and challenges faced by airports. Oliver Wyman (2024).

2.4.4 Comparison of International Standards

The following table and legend provide a summary of the friction levels and test methods for each legislation:

Parameter	ICAO (Doc 9137)	FAA (AC 150/5320-12C)	GACA (GACAR Part 139)
DFL (ASFT @ 65 km/h)	0.72	0.72 (harmonized)	0.72 (ICAO-aligned)
MPL (ASFT @ 65 km/h)	0.52	0.52 (harmonized)	0.52 (ICAO-aligned)
MFL (ASFT @ 65 km/h)	0.42	0.42 (harmonized)	0.42 (ICAO-aligned)
Testing frequency	Traffic-dependent, not prescribed	Traffic-tiered (Table 3-1)	ICAO-consistent, traffic-dependent
NOTAM requirement	Below MFL: mandatory	Below MFL: mandatory	Below MFL: mandatory
Reporting format	Portion averages + 100m minimums	Portion averages	ICAO-aligned
SMS integration	Recommended	Required for Part 139	Required

Although the threshold values are similar for all frameworks, differences exist with respect to the frequency of testing, reporting requirements, and integration into the

overall safety management processes. Currently, no framework exists to address issues related to trend-based analysis, predictive modeling, and integration with traffic data. This study aims to address these research gaps.

2.4.5 The Three-Level Threshold System

The three-tier friction threshold is detailed, representing the criterion that currently governs all decisions regarding friction management and by which the predictive framework developed in this work is measured.

The Design Objective Level (DOL = 0.72) for the expected friction on a new or newly overlaid pavement surface is established as a construction quality objective and an upper limit for friction improvement measurements for various maintenance interventions. This is the expected DOL for new surfaces. As a pavement goes through several years of service and cycles of maintenance, the maximum attainable level of friction on the post-maintenance surface decreases at a rate that is another important pavement condition metric.

The average friction over a running average of a portion of the runway or the minimum 100-meter running average of a portion is below the Maintenance Planning Level (MPL = 0.52). Aerodrome operators should start to consider runway rubber removal or other surface restoration treatments before the friction level reaches the Much Less Favorable level (MFL). The time between the MPL and the MFL is the time to respond or the maintenance planning window and is determined by the rate of friction loss which in turn is determined by the intensity of traffic operation (UK CAA, 2010).

The Minimum Friction Level (MFL) for all assessments is to be set at 0.42. All measurements below this level represent areas where, in addition to assessment, immediate action is required either to restore any deteriorating rubber on the surface or to apply an appropriate surface treatment. The aerodrome operator must also notify the NOTAM authority and issue a suitable NOTAM to pilots warning of this slippery when wet condition.

This research investigated various improvements to the current friction prognosis threshold system used by airport operators, and identified some key limitations of

current practice. The main problem is that the system is binary; it does not allow for assessment of the rate at which the prognosis is decreasing, or assessment of prognosis trend over recent days or months. As models based on recent trends and forecasts become increasingly relevant to aviation safety (UK CAA, 2010), this is a growing issue. For example, a prediction for a runway decreasing at a rate of 0.03/ month at 0.61 (just above MPL) is in a very different position to one which is at 0.61 but trending steady over the last six months.

2.5 Rubber Removal Techniques

Friction surveys performed on numerous asphalt airfields have identified contamination from rubber debris as the primary cause of decreased friction. To combat these problems, numerous methods have been employed by runway operators to remove rubber from the surface. Each method has its own relative effectiveness, operational restrictions, cost, and impact on the pavement. The purpose of this study is to present information relative to each of these items to aid the operator in selecting the most suitable method for rubber removal from runway surfaces.

2.5.1 High-Pressure Water Blasting

High-pressure water blasting is the most common globally used method for removing rubber from pavements, and it is used on all Saudi airports including the airport under study. The detached tires and strips are removed from the pavement using high-pressure water jets with pressures ranging from 8,000 to 40,000 psi. Recent, light deposits are removed at low pressure (8,000–15,000 psi), and heavy, old deposits are removed at high pressure (above 20,000 psi) (Pullen et al. 2014; Watex 2026).

Vehicles fitted with multiple nozzle tips that rotate at high speed are the most common configuration used for water jetting of rubber from airport pavement surfaces. The nozzle tips are mounted on one side of the vehicle or on both sides. Most jetting vehicles are self-propelled, allowing them to move along the pavement surface without the need for tow bars.

Several factors affect the performance of water blasting for removing rubber from pavement. These factors are: water pressure; nozzle angle and distance to surface;

traverse speed; water temperature; water flow; and the age and thickness of the deposits. As effectiveness increases so does the potential to damage the pavement. Fresh deposits are generally easier to remove than older deposits which continue to harden as they polymerize on the pavement surface over time. This reality places a significant maintenance task on the operator. However, light deposits removed frequently require lower cleaning pressures whereas heavier deposits removed less frequently require more aggressive cleaning which could potentially damage the pavement surface (ICAO, 2015).

Ultra-high-pressure (UHP) systems for removing pavement rubber have become more prevalent in recent years as they are able to penetrate deep into the pavement surface texture to remove embedded rubber that lower pressure systems cannot remove. However, high-pressure systems also pose greater risks to the pavement structure than lower pressure systems. This research presents field evaluations of ultra-high pressure water systems designed for rubber removal from runways. While the UHP systems tested in this research were effective for removal of deeply-embedded rubber, they caused changes to the pavement surface texture.

As close to zero as possible is desirable for the removal timing. The cleaning documentation in ICAO Doc 9137 indicates 278 m² per hour per cleaning unit can be cleaned during normal working hours (around 8 hours per day). It is noted that 2 hours per day are required to refill the cleaning solution water tank. For the 900 m x 24 m area of one touchdown zone, this means approximately 21,600 m² can be cleaned in about 100 hours per cleaning unit (ICAO, 2015). A lot of work is required and it is clear that great care is required in coordinating the removal timing for optimal results.

2.5.2 Chemical Treatment

Chemical rubber removal is a method of rubber removal where chemical-based or biodegradable solvent is used to dissolve or soften the removed rubber which is then cleaned or scraped off the surface. This method of rubber removal is effective for moderate amounts of removal and has the least impact on asphalt surfaces when compared to higher pressure water blasting methods. Avion offers a variety of removal products to make rubber removal as effective and safe as possible. Our petroleum-based products have been proven effective at rubber removal for years. Our more recent

developments in environmentally friendly and biodegradable products achieve similar results without harming the pavement, lines or emulsions. Up to 90% of removed rubber can be picked up in one treatment with Avion50 or 2025.

However chemical products for this application have environmental concerns related to runoff contamination and often require extended treatment times for heavy buildups. Although generally replaced by water blasting at most airports for these surface treatments, numerous modern biodegradable products are once again being used for safe and effective de-ice/rubber removal on airport surfaces. ICAO Doc 9137 presents water blasting as the prevailing method for removal of rubber marks from movement area surfaces; however the document describes an alternative approach where the rubber is dissolved and then efficiently washed off the surface with a high-pressure water spray (ICAO, 2015).

2.5.3 Shot Blasting

Shot blasting involves propelling small steel shot at high velocity onto the pavement surface to remove the rubber deposits and a portion of the pavement surface. This is a very effective process for removing heavy contamination from the pavement; however, it is not intended to be a frequent process due to the removal of pavement surface. Typically, shot blasting is applied to surfaces that are heavily contaminated with rubber stripping as well as other elements, and the stripping and additional pavement texture have reached a polished wear.

Shots of high speed steel (HSS) can be a source of FOD (Foreign Object Debris) and be hazardous to other structures such as airport runway lighting. The surface also requires a pre-treatment to form the required groove pattern. This process is not compatible with wet surfaces. The resulting surface is very durable, however the process is significantly more expensive than chemical stripping ($\approx$ \$0.26–\$0.42 per square foot) and would require a longer closure of the runway.

2.5.4 Comparison of Removal Techniques

Characteristic	High-Pressure Water	Chemical Treatment	Shot Blasting
Effectiveness (heavy rubber)	High	Moderate	Very high
Effectiveness (light rubber)	Very high	High	Overkill
Pavement damage risk	Moderate–High	Low	High
Environmental concerns	Moderate (runoff)	Moderate (chemicals)	Low (but FOD risk)
Cost per application	Moderate–High	Low–Moderate	High
Required equipment	Specialized vehicle	Basic application gear	Specialized vehicle
Runway closure duration	Long (100+ hours/TDZ)	Moderate	Long
Marking preservation	Poor (can remove)	Good	Poor (removes)
Frequency tolerance	Moderate	Good (less damage)	Low (material removal)

2.5.5 Engineering Risks of Rubber Removal

All rubber removal techniques impose some degree of mechanical stress on the pavement surface, and repeated removal cycles cause cumulative damage that progressively degrades the pavement's intrinsic friction capacity. The principal damage mechanisms include:

Binder stripping: High-pressure water can strip the asphalt binder from around aggregate particles, loosening them and reducing the cohesion of the surface course. This is particularly problematic for aged pavements where the binder has already hardened and become brittle due to oxidation—a condition prevalent at Saudi aerodromes due to the extreme thermal and UV environment.

Aggregate dislodgement: Repeated high-pressure treatment can dislodge surface aggregate particles, creating voids in the pavement surface that reduce both macrotexture quality and structural integrity. Once aggregate particles are lost, they cannot be replaced without resurfacing. The loss of well-polished-resistant aggregates from the surface course permanently reduces the pavement's friction potential.

Microcracking: The impact of high-pressure water jets can initiate microcracks in the surface course, which propagate under subsequent traffic loading and thermal cycling, accelerating the overall deterioration of the pavement. In the Saudi context, where diurnal temperature ranges can cause significant thermal stress, these microcracks propagate rapidly.

Macrotexture reduction: While rubber removal restores drainage-critical macrotexture in the short term, the cumulative loss of binder and aggregate from repeated treatments progressively reduces the overall texture depth, diminishing the pavement's long-term drainage capacity.

The cumulative impact of these damage mechanisms manifests as declining friction recovery after successive rubber removal cycles. Where the first removal on a new pavement may restore friction to near the Design Objective Level (0.72), the tenth or twentieth removal on the same pavement may only restore friction to 0.70 or 0.65, because the pavement's surface has been degraded to the point where its intrinsic

friction capacity has been permanently reduced. This phenomenon of diminishing returns is the central engineering challenge in long-term friction management and provides a key motivation for the predictive approach advocated in this study (Wambold et al., 1995; Sales et al., 2021).

2.6 Pavement Deterioration Mechanisms

Runway pavement deterioration occurs for a complex array of traffic, environmental and maintenance related factors and as the pavement structure undergoes change, so the surface texture of the surface course changes affecting the friction performance. The aim of this work is to investigate the key factors affecting friction performance and how these change with pavement deterioration.

Traffic-induced wear and polishing: In addition to traffic-induced wear of the tyre and pavement surface, traffic also induces polishing of the pavement surface. The polished surface of the pavement wears less quickly than the rough surface but has a reduced microtexture which in turn leads to a reduction in low-speed friction. The extent of polishing increases with the number of passes made by tyres on the pavement surface. Softer aggregate types, such as limestone, are more prone to polishing than harder types such as basalt. An assessment of the surfaces at Saudi aerodromes found the calcereous aggregates were subject to a greater decrease in friction compared to igneous aggregates (granite or basalt). The interaction between the aircraft tyre and pavement is not limited to rubber deposition from tyre wear. Significant mechanical wear of the pavement surface also occurs. Larger aircraft create higher pavement contact pressure resulting in increased pavement polishing.

Oxidative aging: The oxidation of asphalt binder is an ongoing process and it continues to react with oxygen in the air and ultraviolet radiation from sunlight as time elapses. Oxidized asphalt binder becomes hard and nonelastic, loses viscosity, and becomes inefficient in its bitumen-aggregate interaction. The rubber removed from airport surfaces using high-pressure water can also leach the aged binder from the pavement surface. Recent molecular dynamics computer simulation results indicated that oxidative aging significantly increased the glass transition temperature of asphalt binders, approximately by 30 K (Fini and Cao, 2021, Transportation Research Record,

2581, 104–111). Increased glass transition temperature of aged binder increases its susceptibility to thermal cracking. The oxidative aging rate is directly related to the pavement surface temperature; the test results indicate that the rate of oxidative aging is approximately doubled with each 10°C increase in temperature. Therefore, Saudi aerodromes can expect to have oxidized aged binders regardless of the age of pavement. 2009).

Thermal cycling and stress: Thermal stress is one of the major deterioration factors in Saudi Arabia. The pavement surface temperature at Saudi aerodromes in summer is sometimes reaching up to 70°C. Therefore, there are very large thermal gradients between surface and subtiercentric Schichten. Studies on flexible pavements in Saudi arid environment indicated that temperature varied from 3°C to 72°C, with a maximum daily temperature gradient of 15°C for rigid pavements (Al-Abdul Wahhab & Balghunaim, 1994). The recurrent daily thermal cycling induces fatigue stresses in the surface layer and leads to various type of cracks and delamination. In this study, the differences of asphalt binder aging induced by various climate conditions have been investigated. Results showed that UV–thermal coupling is the most severe degradation; UV radiation and temperature difference are the major environmental aging factors in arid environments. The elevated construction temperature and UV radiation in warm-mix asphalt construction create ideal conditions for asphalt binders to oxidize and harden, increasing asphalt stiffness, leading to cracking, and a loss of surface texture during traffic operation and construction maintenance events.

It is well known that Saudi Arabia experiences very heavy downpours for short periods in addition to introducing moisture into the pavement through the water used in the rubber removal process and moisture in the pavement surface through the tests conducted to determine pavement friction. Moisture entering into existing cracks or debonded areas at the surface course /plant mix interface can remove the asphalt binder from the surface of the aggregate. The runways in Saudi Arabia experience high humidity levels, which accelerates the development of sulfides in asphalt binder leading to an increase in the sulfoxide groups within the binder. In addition to this, lighter petroleum derived distillate fractions are leached from the asphalt matrix, resulting in asphalt hardening.

Runways surfaces in Saudi Arabia are subject to significant degradation by sand. The fine grains of sand get stuck to the surface of pavement, wearing them down. Moreover, the abrasive nature of sand that enters cracks in pavement surfaces causes them to widen, allowing water to infiltrate the pavement through those cracks and subsequently deteriorate the subbase.

The deterioration–friction feedback loop: The relationship between deterioration and friction management is a positive feedback loop that is important to understand in this study. Deteriorated pavement has a higher potential for storing rubber, as the rough surface is replaced by a smoother surface that provides a better surface for rubber to adhere to. More frequent removals of rubber may be required to maintain adequate friction, which in turn can deteriorate pavement. This feedback loop includes the relationships between pavement condition and the rates of friction loss and the process required to restore friction, and thus knowledge of the current pavement condition is important to effective friction management.

2.7 Traffic Influence on Runway Performance

Air traffic is the single most significant factor affecting both skid resistance degradation and deterioration due to wear. Additionally, the effect of traffic on the friction properties of pavement can be complex and influenced by several factors, including the intensity of traffic, mix of fleet operating on the pavement, and other operating characteristics.

Landing frequency and rubber deposition rate. The landing frequency is a parameter strongly affecting the rubber deposition rate. The hundreds or thousands of landings between the cycles of de-rubberizing operations create a contamination layer on the pavement surface decreasing gradually the friction level. The high landing frequency, in fact, results in a faster decreasing of the friction level and in a need of closer surveillance and more frequent de-rubberizing operations. The friction testing frequency is established by the FAA's Advisory Circular AC 150/5320-12C, and it is related to the annual average jet operations. In the previous researches, De Luca et al. (2016) correlated the results obtained by a Grip Tester to some surface parameters of pavements and, using the friction decay functions obtained through the analysis of data

collected before and after the de-rubberizing process, it has been possible to schedule the traffic-based maintenance activities.

Aircraft weight and landing gear configuration: The weight category of the aircraft will impact the rubber deposition during the tire spin-up process. Typically, heavier aircraft have higher tire operational loads and larger diameter tires than their lighter counterparts. This results in greater friction during the spin-up process and increased tire temperature resulting in higher rubber deposition per landing. The ICAO established weight categories for use in weighting traffic intensity. For example, a single Category E landing (e.g. Boeing 777 or Airbus A330-400) can deposit more than twice the rubber deposited by a Category C narrow body (e.g. Boeing 737-800 or Airbus A320-200). The friction deterioration rate will also be impacted by the specific fleet mix.

The type of landing gear of an aircraft can affect the lateral distribution of rubber from tires onto the runway surface. For wide-body aircraft, the dual-tandem main gear configuration typically produces four roughly parallel tracks on the pavement. In contrast, narrow-body aircraft often have single-axle dual-wheel main gear configurations, which typically produce two distinct tracks. The pattern of contamination created by these tracks, combined with the typical pattern of touchdown locations along the length of the runway, defines the overall contamination pattern.

Saudi airports experience a marked increase in air traffic during the two main Islamic pilgrimage seasons. At the case study airport, this translates into an increased landing movement rate, at times reaching 50-100% above the average daily landing movements. Notably, within a period of a few weeks in August 2025, more than 6.8 million passengers used the four major airports in Saudi Arabia for Umrah and Hajj worship (Saudi Gazette, 2025). The ‘rush’ to these seasons results in a dramatic increase in the rate of rubber removal from airfield pavements that frequently exceeds the ability of airport maintenance personnel to respond. Further, the high-demand period presents significant challenges to airfield maintenance personnel to maintain as much as possible of the airfields in operation, thus limiting the time available to address any detected issues with component runtime.

ICAO traffic-based maintenance frequency guidance: ICAO in its Circular 138: Maintenance of Runway Visual Range (RVR) Systems provides general guidance on correlating traffic volume on a runway with the appropriate friction surface testing frequency. However, the Circular does not require the development and incorporation of the traffic data into a maintenance planning model to calculate the traffic-based frequency and this is also not a requirement in the current GACA Airfield Lighting Certification Manual. ICAO guidance does not include traffic in its recommendation for the traffic-based maintenance frequency, however the FAA includes traffic in the traffic-based testing frequency in the FAA Airfield Lighting Technical Manual AC 150/5320-12C, Table 3-1. The traffic categories in this table are used as static characteristics and not dynamic variables in a predictive model. The objective of this research is to use traffic data in the development of a predictive model to determine the appropriate maintenance frequency.

Friction: Runway-end usage distribution – The traffic usage on the ends of runways creates friction in pavement surfaces that needs to be monitored by airport maintenance personnel. For example, one end of a runway might have rubber deposited mainly in the touchdown zone, whereas the other end might have rubber deposited mainly at the departure end. Even in prevailing wind conditions, both landings and takeoffs might occur on the less-used end of the runway during periods of wind shifts or calm weather. As a result, there is a varied need for different maintenance activities along the length of the runway, with most emphasis on the runway end that is used for landings. This study documents and analyses the runway-end usage asymmetry at an airport with prevailing winds.

2.8 Maintenance Strategies

This study organizes runway friction maintenance practices along a spectrum from fully reactive to fully predictive, and discusses each approach in turn. The study then explores each of these categories in a comparative analysis, and includes a discussion of preventive (time-based) maintenance practices as an intermediate category.

2.8.1 Reactive Maintenance — Current Practice

Friction management at most commercial airports is achieved by a reactive maintenance approach (corrective/threshold-based maintenance – RM). Friction is measured on a regular basis and when friction is detected below a pre-determined threshold, a maintenance action is performed and verified before further action is taken (i.e. rubber removal). The same approach is adopted at the Saudi airports.

Reactive maintenance has a number of advantages, including simplicity and clarity of decision, compliance with government regulations, and less analytical complexity since no historical database, trend or predictive analytical capability is required. Only periodic measurements need to be made and compared to threshold levels.

While size may matter from a services to investors perspective, the disadvantages are substantial and well-documented in the literature on the asset management industry.

1. Safety timing: Friction can be monitored just prior to the worst friction levels putting components at risk, with maintenance scheduled at that time. The actual worst friction would be least safe, with the smallest margin for error. Plus there is always some time lag between when the measurement is made and when maintenance is actually performed.
2. Measurement – driven timing: Currently, maintenance timing is typically based on the test schedule. This can result in detection being delayed (i.e. friction is deteriorating faster than planned between tests) or unnecessary testing (i.e. friction is deteriorating at a slow rate during periods in between tests).
3. pavement impact blindness: The method does not account for all the effects of repeated cycles of maintenance activities on the condition and performance of pavement structures, resulting in potential over-maintenance as the removal threshold is reached or ‘triggered’ without optimisation for minimum pavement damage.
4. Emergency: More urgent, more disruptive and more costly than planned removals. Because emergency removals are caused by a pipe surpassing a certain threshold, they typically have to be done as quickly as possible while the pipe is still active, and thus cannot be scheduled to take advantage of optimal operational windows.

5. Lack of future planning. While some operators will have a rough idea when they might next need to remove the rubber, in practice, this is unlikely to be coordinated with the next suitable flight, or with other maintenance / resurfacing activities that could be undertaken around the same time.

2.8.2 Preventive Maintenance

In contrast to reactive or condition-based maintenance practices, preventive maintenance, also known as time-based or interval-based maintenance, schedules maintenance activities based on fixed time intervals. For example, in the airport management context, determining the optimal time to remove worn-off rubber from a runway surface to restore proper friction might be based on a schedule (e.g. every six months or after a certain number of landings) regardless of current friction levels.

A further advantage of the Preventive Maintenance approach is that the service life between measurements is not shortened because of the risk of threshold exceedance. However, the opposite risk of over-maintenance cannot be disregarded: that of removing the pavement from service while it would have been sufficient to let it complete safely its designed life cycle, with additional costs of the maintenance intervention and with damage to the removed pavement.

Existing airport operations are mostly in a mixed mode, complying with regulations to conduct periodic friction tests, removing rubber markings on a “best judgment basis” with a periodicity, conducting test lengths and additional maintenance when necessary. There is significant room for improvement by moving to an integrated, analytical and predictive model.

2.8.3 Predictive Maintenance — Data-Driven Approach

Friction systems undergoing maintenance will have Predictive Maintenance performed by forecasting future operational data and schedules based on historical and trending data. The system will require more advanced data management for historical friction test data, traffic and other pertinent information as well as maintenance records and history. The reward of this approach will be well worth the enhanced data management system.

This PD-Man Technical Note outlines the fundamental basis for predictive maintenance of friction on runways.

6. Trend projection: The rate of decrease of friction can be monitored over several cycles and trended forward to predict when the Minimum Productive Load (MPL) and Minimum Friction Load (MFL) will be reached. This information provides a time-to-threshold.

7. 7. Traffic-based prediction: Since friction degradation is largely due to rubber from deteriorating runways and touch and go landings, it can be predicted based on cumulative traffic loading between maintenance cycles. Intensities of traffic (i.e., landings) between maintenance interventions can be used to develop a schedule for traffic responsive maintenance interventions.

8. Condition-aware intervention: Utilize pavement condition measures (such as post-removal friction recovery and baseline friction trends) as the pavement ages and undergoes various quantities of removals, application rates, and aging. Intervene by reducing removal pressure, increasing the interval between removals, or adding a overlays or other treatments.

9. Optimization: Use the model to make the most of limited resources by simultaneously trying to 1) minimize safety risk by maintaining an adequate friction margin, 2) reduce pavement damage by removing lighter contamination with a less aggressive treatment, 3) reduce costs by reducing the number of interventions over time, and 4) minimize operational disruption by scheduling maintenance during low traffic periods.

Predictive maintenance, a practice widely adopted in the infrastructure asset management literature, has been demonstrated to reduce life cycle costs associated with maintenance by 15–30% or more while providing similar or improved asset conditions. Rosati et al. (2022) presented the development of an IoT and machine learning–based framework for predictive maintenance incorporating physical sensors, digital twins, and a decision support system. The results showed potential to achieve on-time maintenance while maximising the lifespan of equipment. Su et al. (2025) applied decision tree techniques to develop a novel, data-driven methodology for the

classification and severity assessment of pavement distress in airport pavements, and determination of appropriate maintenance actions.

Published examples of predictive maintenance applied to runway friction management are not available. However, there is no lack of data to be ‘mined’ at an aerodrome. Available are trends in friction, traffic flow, and historical maintenance information. However, there are more significant barriers to the application of predictive maintenance than those associated with data availability (i.e., information), specifically those related to data integration, analysis, and optimisation. In this paper, a practical framework for the application of predictive maintenance for runway friction management is presented using available real-time data from the management systems routinely used at an aerodrome. The framework is then illustrated using actual data from a study airport.

2.8.4 Comparison and Evolution

Characteristic	Reactive	Preventive	Predictive
Trigger for action	Threshold exceedance	Fixed interval	Trend projection
Data requirements	Current measurement only	Historical intervals	Full historical database
Safety margin timing	At minimum when detected	Buffer but not optimized	Continuously maintained
Pavement impact consideration	None	None	Integrated
Traffic responsiveness	None	None	Real-time
Cost optimization	None	Partial	Full lifecycle

Operational planning capability	Emergency response	Basic scheduling	Advance coordination
Implementation complexity	Low	Low	Moderate–High
Regulatory alignment	Full (minimum compliance)	Full	Full (exceeds minimum)

There is a growing trend towards moving from a reactive to a predictive maintenance practice in various industries including Power Generation, Transportation and Manufacturing as well as aviation services such as power unit maintenance for ground equipment. The aviation industry has a good safety culture however its practices relating to predictive maintenance are slow. Air transport regulations were established with a focus on achieving compliance rather than optimising pavement management practices through well defined thresholds. The research study aims to assist the evolution of predictive friction management practices at Saudi aerodromes by formulating a framework to guide practice, and verifying its implementation.

2.9 Decision Support Systems in Aviation

Decision Support Systems (DSS) used for aviation maintenance have matured from simple threshold comparisons of basic parameters to more complex multi-parameter analytical models utilizing multi-source data to support a variety of maintenance-related decisions.

State of the art of current pavement management systems: While pavement management systems for runway infrastructure are quite mature, Airport Pavement Management Systems (APMS) are the most developed Decision Support Systems (DSS) for airfield management. Most of the currently implemented APMS are integrated DSS that include both Pavement Condition Index (PCI) and structural information from falling weight deflectometers (FWD) and other ground based NDTs and historical maintenance records to support management decisions related to

maintenance and rehabilitation actions. Specifically, an airport pavement maintenance decision-making system with condition cases optimization for solving the problem of multi-facility and multi-year management optimization within a given budget was proposed by Roh et al. (2023). A practical application of APMS at Cagliari Airport was presented by Ragnoli et al. (2021) highlighting how the APMS is used as a strategic tool to define technically and economically optimal pavement management plans.

Currently, the primary inputs to APMS frameworks are not friction trend data, traffic loading data, or rubber removal data. As such, the pavement condition index, a widely used measure of pavement condition within APMS, does not measure or predict friction loss for maintained pavement, potentially leading maintenance decisions to improve structural performance but decrease friction.

Airport management has increasingly evolved into a data-driven discipline and how to manage data from different sources and make effective analysis has become one of the hot topics among researchers and practitioners. This study developed a Markov probability model for predicting the remaining service life of civil airport rigid pavements on the basis of historical data and applied it to predict the remaining life of the existing airfield pavements. The results show that the model can predict the life of airport rigid pavement from the discontinuous related data by using survival analysis method, which can guide airport management to decide whether to perform maintenance within the expected cost. In order to achieve the optimal maintenance plan, Arena et al. (2021) established a decision support system for selecting predictive maintenance strategies based on machine learning for overcoming traditional maintenance techniques mainly based on fixed threshold values. The results have demonstrated that data-driven approaches perform better than the rule-based traditional thresholding methods in terms of maintenance performance on industrial equipment (such as pumps, valves and gearboxes); similar results are expected for airport maintenance applications.

New developments in machine learning and AI have been explored in relation to artificial intelligence assisted friction management on the airport runway. In Aquino et al. (2025), deep learning was applied to classify satellite images into corresponding

pavement friction levels on the runway surface. While initial results are promising and demonstrate the potential for a highly scalable, automated pavement friction management system, work is still needed to fully integrate such a system with existing management frameworks and hardware. In Malekloo et al. (2024), deep learning was applied to the analysis of dashcam videos in order to detect and assess pavement visual distresses on airport runways. The results of this analysis reveal the potential for cost-effective, automated visual pavement distress detection and condition assessment. These emerging tools could complement the existing chain flexure measurement system (CFME) to obtain friction measurements in real time to enhance the predictive capabilities of the existing predictive maintenance system.

While current DSS frameworks address aspects of runway friction management, there are significant gaps in each. For example, current practices compare friction measurements to threshold values, manage air traffic on the basis of current traffic, assess pavement condition for structural integrity, remove rubber on the basis of historical practices and current trends, and coordinate with maintenance personnel on the basis of current trends. The framework proposed in this research, therefore, addresses all five critical aspects of friction management – friction measurement trends, traffic, rubber, pavement, and maintenance – and creates a single framework for runway friction management that integrates the information from each.

2.10 Research Gap

While individual knowledge domains are more than adequately addressed in the literature, there is a lack of integration of multiple knowledge domains. This paper reviews current practices with respect to runway friction management, highlighting conceptual and practical deficiencies. Alternative approaches are suggested for a more holistic understanding of winter runway operations.

Friction management on the runway suffers from a form of conceptual fragmentation in that existing knowledge is dispersed amongst a variety of disciplines.

- Friction measurement and standards: There are established standards and methods for friction measurement following a runway incidence in the wake of an incident reported by an aircraft on final approach in landing (IAA, 2012; ICAO, 2015;

FAA, 2016; GACA, 2023). Currently there are established criteria for when an operator will be informed that runway friction is below a specific value; however there are no existing tools which enable the operator to foresee when this occurs (UK CAA, 2010, 2015, 2016).

- The mechanisms behind the accumulation and deposition of rubber on tires have long been established (Gopal & Timm, 2019; Horne & Dreher, 1963; De Luca et al., 2016). In addition to this, empirical models that correlate specific traffic activities with reduced friction have been established for particular airports. However, models that quantify the correlation between increased traffic intensity and loss of friction for particular airports have not been found in the literature specific to the Middle East.
- The various techniques for the removal of rubber from the pavement surface have been documented in terms of their immediate effectiveness (Pullen et al. 2014; ICAO 2015; Sales et al. 2021); however, there is no practice in place to monitor or record the cumulative long-term affects on pavement degradation over several maintenance cycles at an airport, as is addressed in the current study that describes the compounding effects of the degradation cycle over several cycles.
- Pavement deterioration models for general pavement management system (PMS) have been studied and developed by many researchers (Huang, 2012, Shahin, 2005, etc.). Some studies also focused on deterioration models for different environmental conditions such as temperature (Al-Abdul Wahhab & Balghunaim, 1994). However, none of them were combined with friction management data and/or rubber removal history data. In practice, pavement management system and friction management system work independently.
- While Predictive Maintenance strategies are well established for general Infrastructure Maintenance (de Solminihac et al. 2018, Rosati et al. 2022, Arena et al. 2021), and are starting to be applied to the management of airport pavements (Roh et al. 2023, Su et al. 2025, Wei et al. 2022), the application of these strategies to managing runway friction remains an unexplored domain, particularly with respect to the integration of friction trends, traffic data and pavement condition.

Although several studies and researches have been conducted on improving aerodrome operations, no single study has been undertaken to address all relevant aspects of the problem in a holistic manner and to develop a comprehensive decision-support framework for effective aerodrome management. In the context of improving runway friction management over the life cycle of pavement, Baimukhametov and White (2025) identified the need for improvements in measurement methods and associated data interpretation for assessing friction on airports, and proposed methods for friction management. However, an integrated framework for day-to-day runway friction management was not developed. De Luca et al. (2016) established friction decay models relating friction performance to traffic exposure, but other key elements influencing aerodrome friction, namely rubber removal from the pavement surface and friction deterioration, were not treated in their work. For structural condition-based airport pavement maintenance decisions, Su et al. (2025) utilised a data-driven methodology; however, their methodology was not aimed at achieving optimal friction levels.

The available published literature on this topic is almost entirely without Saudi or Middle Eastern relevance. While many practitioners and researchers around the world including those based in North America, Europe and East Asia have developed techniques and equipment to manage friction on wet runways, there is a distinct lack of data within the published literature in relation to actual operational friction readings obtained from Middle Eastern airports including those based in Saudi Arabia. While many of the available techniques and solutions may be relevant to use on Saudi airports, they require to be further researched and validated for local conditions. There is a particular need for longer duration studies into friction on Saudi pavements, the characteristics of deposited rubber, pavement degradation over time and associated maintenance interventions.

While the individual processes of the degradation cycle have been studied for many years, the complete cycle itself has not been recognised, named or studied as a single phenomenon. This paper discusses the cycle of rubber accumulation degrading surface friction, removal damaging the pavement, and the damaged pavement acting as a conduit to increased rubber accumulation. The literature is drawn upon, as well as a

longitudinal data set from an airport, to establish the complete cycle and determine the rate of degradation. Management strategies are then proposed to address the problem.

This research inquiry investigates a range of organisational and related factors that may affect the implementation of virtual learning environments.

10. Validation of the developed model by applying it on a Saudi airfield and the analysis of the outcome by comparing the runway traffic parameters with actual data. The outcome would then be correlated with the history of usage and the level of wear as well as with the results of the maintenance operations conducted to reduce strip fatigue.

1. Shows the deterioration cycle over time with data on the after-removal post-friction restoring efficiency for several maintenance cycles.

2. Comparison of reactive and predictive maintenance using measured friction deterioration rates and effectiveness; assessment of safety, cost and pavement preservation benefits using runway surface deterioration rates.

3. Development of an integrated decision-support system for determining the optimal timing of maintenance activities such as molasses application or lane closure to address hazards such as water on the runway, by linking real-time traffic and real-time friction information to existing pavement data.

This research incorporates data from real world sources into previously independent domain specific knowledge bases to form a body of empirical knowledge. In contrast to traditional research which provides a theoretical solution to a theoretical problem, the results of this research offer a means of uniting theoretical models and real world practice, enabling aerodromes, particularly in the under-studied Saudi environment, to increase their turn-around time and so become more profitable. The results of this research should be of use to practitioners at all aerodromes in the region, providing a practical tool for local managers.

Chapter 3 METHODOLOGY

1.1. Research Design

For confidentiality purposes, runway designations and certain operational identifiers have been anonymized in this study. The analysis remains fully representative of actual operational conditions.

This study employs a quantitative, longitudinal, case-study research design to investigate the interrelationships among air traffic characteristics, runway friction performance, rubber removal practices, and pavement condition at a major Saudi international airport (hereinafter referred to as "the study airport") in a major international airport in Saudi Arabia. The design integrates elements of applied research with a descriptive-analytical orientation: it seeks not only to describe observed patterns in operational data but also to analyse the causal and temporal relationships that produce those patterns and to derive actionable decision-support recommendations from the findings.

Three methodological commitments distinguish this design. First, the study is quantitative. The variables of interest—friction coefficients, air traffic counts, aircraft masses, maintenance event dates—are directly measured and recorded in standardised operational documentation. No surveys, questionnaires, interviews, or other primary data collection instruments are employed. The data are extracted from existing records produced in the normal course of aerodrome operations, making this a documentary analytical study in the tradition of secondary data research (Bryman, 2016).

Second, the study is longitudinal. Rather than analysing a single friction test in isolation, the research tracks friction performance across ten unique test dates spanning approximately three years (February 2023 to January 2026). This temporal depth is essential for identifying trends, calculating degradation rates, evaluating the effectiveness of maintenance interventions over successive cycles, and detecting the compounding degradation phenomenon that emerges only when multiple maintenance cycles are observed sequentially. Cross-sectional designs, which would capture friction at a single point in time, cannot reveal the dynamic processes—accelerating degradation, diminishing rubber removal returns, and pavement lifecycle effects—that constitute the study's core contributions.

Third, the study adopts a case-study approach. The investigation concentrates on a single runway at a single airport, enabling the depth of analysis necessary to disentangle the interacting variables that influence friction performance. The case-study methodology is appropriate when the research seeks to understand a phenomenon within its real-world operational context, when the boundaries between the phenomenon and the context are not clearly separable, and when multiple sources of evidence are available for triangulation (Yin, 2018). Runway friction management at the study airport satisfies all three conditions: friction behaviour is inseparable from the airport's specific traffic patterns, climate, pavement characteristics, and maintenance practices; and the study draws on friction test reports, air traffic records, and pavement condition observations as convergent data streams.

The appropriateness of this design is further supported by the research questions, which require longitudinal tracking (How does friction change over time? How do successive rubber removal events compare?), quantitative measurement (What are the degradation rates? What is the correlation between traffic and friction decline?), and contextual depth (How do seasonal traffic patterns interact with maintenance scheduling constraints?). Alternative designs—such as cross-sectional surveys of multiple airports or experimental designs manipulating maintenance parameters—would sacrifice the temporal and contextual depth that the research questions demand.

1.2. Unit of Analysis

The primary unit of analysis Runway X/Y at a major Saudi international airport (hereinafter referred to as "the study airport"), the study city, Saudi Arabia. This runway measures 4,335 metres in length and 60 metres in width, with a surface composition of concrete for the first 250 metres from each threshold and asphalt for the remainder. It operates as the main runway in a main/standby configuration with Runway A/B (3,050 m × 45 m), handling the overwhelming majority of the airport's commercial traffic.

The decision to focus on a single runway provides several analytical advantages. First, it controls for inter-runway variability in pavement type, age, maintenance history, and traffic exposure, enabling clean attribution of friction changes to the variables under investigation rather than to confounding facility differences. Second, it allows the study to achieve granular analytical depth—examining friction at three lateral

offsets, in both runway directions, across three runway portions, and over ten test dates—that would be impractical if the scope included multiple runways or airports. Third, the study airport's status as the one of the busiest airports in Saudi Arabia, serving over 10 million passengers in 2024 and experiencing distinctive seasonal traffic surges driven by Hajj and Umrah pilgrimages, makes it a substantively significant case whose friction management challenges are representative of the broader issues facing high-traffic aerodromes in climatically demanding environments.

The single-runway, longitudinal case-study design aligns with Yin's (2018) criteria for case-study appropriateness: the phenomenon under investigation (friction degradation and maintenance effectiveness) cannot be separated from its operational context, and the research questions require detailed understanding of processes that unfold over time rather than statistical generalisation across a population of runways. The depth-over-breadth trade-off is deliberate and justified by the study's objectives.

It is important to note that the study focuses exclusively on Runway X/Y and does not include data from the standby Runway A/B. The two runways differ in dimensions (3,050 m × 45 m for Runway A/B), pavement composition, traffic volume (Runway A/B receives less than 1% of total landings), and maintenance history, and combining data from both would introduce heterogeneity that could obscure the relationships under investigation. Similarly, the analysis confined to the RWY X and RWY Y ends of the study runway; the negligible traffic on RWY A and RWY B (combined less than 1% of total operations) does not materially affect friction conditions on Runway X/Y.

1.3. Data Sources

The study utilises three primary categories of operational data, supplemented by qualitative observations from airport operations personnel. All data were generated in the normal course of aerodrome operations in compliance with GACA regulatory requirements and ICAO standards.

1.3.1. Friction Test Reports

Friction test reports constitute the primary data source for the study. A total of 12 reports covering 10 unique test dates were obtained, spanning the period from February 7, 2023, to January 13, 2026. Two pairs of duplicate reports were identified

(Reports 2 and 8, both documenting the June 19, 2024, test; and Reports 3 and 4, both documenting the October 21, 2025, test), reducing the effective dataset to 10 unique friction surveys.

Each friction test was conducted using a certified Airport Surface Friction Tester (ASFT) vehicle, a certified ASFT vehicle, operating at the ICAO standard test speed of 65 km/h with a self-wetting water film delivery system engaged. Six test passes were performed per survey: three passes in the RWY Y direction (heading 350°) and three passes in the RWY X direction (heading 170°), at lateral offsets of 3 metres, 6 metres, and 9 metres from the runway centreline.

Each report documents the following variables:

- **Environmental conditions:** ambient temperature (°C), relative humidity (%), and wind speed (km/h) at the time of testing.
- **Equipment configuration:** tyre type and inflation pressure, test speed, and water film status.
- **Per-pass friction data:** for each of the six passes, the friction coefficient measured at 50-metre intervals along the entire 4,335-metre runway length, yielding approximately 87 individual measurements per pass.
- **Portion averages:** the arithmetic mean friction coefficient for each runway third (Portion A, B, and C) within each pass.
- **Pass summary statistics:** the overall pass average friction coefficient, the minimum recorded value, and the maximum recorded value.
- **Overall summary:** the overall average across all six passes, the overall minimum and maximum, and the ICE percentage indicator.

An important methodological consideration is the variation in test tyre configuration across the study period. Reports 10 and 11 (February and March 2023) employed the T49 tyre at 7.0 bar inflation pressure. Reports 9 and 12 (August and September 2023) employed the ASTM tyre at 7.0 bar. Reports 1 through 8 (January 2024 onwards) employed the ASTM tyre at 2.1 bar. The change to the ASTM tyre at 2.1 bar aligns with updated industry standards and is the configuration recommended by the equipment manufacturer for operational friction assessment. While the tyre change introduces a potential confound when comparing early and later tests, the transition

occurred before the critical study period (2024–2026) during which the most significant degradation patterns were observed, and the longitudinal trends within the ASTM 2.1 bar period are internally consistent.

1.3.2. Air Traffic Data

Air traffic data were obtained from the aerodrome's air traffic management system in the form of three Microsoft Excel workbooks covering the periods January 2023 to December 2023, January 2024 to October 2024, and May 2025 to October 2025. The data are aggregated at the monthly level and report the number of landing operations by runway end (RWY X, RWY Y, RWY A, and RWY B), by aircraft type, and by maximum takeoff weight (MTOW).

For each month, the dataset provides:

- **Landing counts by runway end:** enabling the calculation of directional traffic distribution and the identification of the predominant landing direction.
- **Aircraft type distribution:** enabling the characterisation of the fleet mix and the identification of the most frequently operating aircraft types.
- **Aircraft MTOW data:** enabling the calculation of cumulative mass loading on the runway, which serves as an alternative metric for rubber deposition potential and pavement loading.

The traffic data cover 28 months of actual observations across the study period. A gap exists for the months of November 2024 through April 2025 and November 2025 through January 2026, for which no recorded data were available. These missing periods are addressed through the estimation methodology described in Section 3.5.5.

1.3.3. Rubber Removal Records

Formal rubber removal records documenting specific operational parameters (water pressure, number of passes, traverse speed, chemical agents) were not available as standalone documents. Instead, rubber removal events were identified indirectly from the friction test data using a rule-based approach: where friction values improved between consecutive tests, a rubber removal operation was inferred to have occurred in the intervening period. This inference is operationally valid because friction does not spontaneously increase on a runway under continued traffic loading; an

improvement in measured friction between consecutive surveys necessarily indicates that a maintenance intervention restored the surface condition.

The operational workflow at the study airport, as confirmed by airport operations staff, follows a standard sequence: (1) a friction test is conducted and results are analysed; (2) if friction falls below acceptable levels, rubber removal is scheduled; (3) the rubber removal operation takes approximately 7–10 days; and (4) a confirmation friction test is conducted on the last day of the rubber removal operation to verify its effectiveness. The post-removal test thus serves as both the confirmation of maintenance effectiveness and the baseline for the next degradation cycle.

Applying this rule to the 10 test dates, three confirmed rubber removal events were identified (between Tests 1 and 2, between Tests 4 and 5, and between Tests 7 and 8). An important exception to the rule applies to the final two test periods (Tests 9 and 10): despite friction values declining to levels that would normally trigger rubber removal, no improvement was observed because severe asphalt deterioration prevented the rubber removal operation from being performed—the application of the necessary water pressure would have caused further damage to the compromised pavement surface.

1.3.4. Pavement Condition Observations

Qualitative observations regarding pavement condition were obtained from airport operations staff responsible for runway maintenance at the study airport. These observations documented the progressive deterioration of the asphalt surface on Runway X/Y, including evidence of binder stripping, aggregate dislodgement, surface ravelling, and macrotexture loss. The most significant observation was the determination, made in the second half of 2025, that the asphalt pavement had deteriorated to the point where rubber removal using high-pressure water could no longer be safely performed without risking further damage to the pavement structure. This qualitative assessment is corroborated by the quantitative friction data, which show a failure to improve between the October 2025 and January 2026 tests despite the operational need for rubber removal.

1.3.5. Note on Tyre Type Changes

The change in test tyre configuration during the study period warrants specific methodological attention. The transition from the T49 tyre (7.0 bar) to the ASTM tyre

(7.0 bar) in mid-2023, and subsequently to the ASTM tyre at the reduced 2.1 bar inflation pressure from January 2024 onwards, reflects the airport's adoption of updated equipment standards. The ASTM tyre at 2.1 bar is considered the current industry standard for ASFT friction testing and produces readings that are directly comparable to the ICAO threshold values (DOL = 0.82, MPL = 0.60, MFL = 0.50). Tests conducted with the T49 tyre and with the ASTM tyre at 7.0 bar are included in the longitudinal analysis to provide the fullest possible temporal coverage, but the primary analytical conclusions—particularly regarding degradation rates and ICAO compliance—are drawn from the six tests conducted under the standardised ASTM 2.1 bar configuration (January 2024 to January 2026).

1.4. Study Population and Sample

The **target population** for this study comprises all commercial aerodromes in the Kingdom of Saudi Arabia that operate runways subject to rubber contamination from landing operations. As of 2025, this population includes 29 airports certified by the General Authority of Civil Aviation (GACA), ranging from major international hubs (King Abdulaziz International Airport, Jeddah; King Khalid International Airport, Riyadh) to regional facilities with lower traffic volumes.

The **study sample** consists of a single purposively selected case: Runway X/Y at the study airport, the study city. Purposive sampling is appropriate for case-study research where the objective is analytical depth rather than statistical representativeness (Yin, 2018). the study airport was selected on the basis of the following criteria:

1. **Traffic volume:** the study airport is the one of the busiest airports in Saudi Arabia, with sufficient traffic to generate meaningful friction degradation patterns within observable timeframes.
2. **Seasonal variation:** The airport's traffic profile, characterised by pronounced Hajj and Umrah peaks, creates natural variation in rubber accumulation rates that enhances the analytical value of the dataset.
3. **Data availability:** Comprehensive friction test reports, air traffic records, and operational observations were accessible for the study period.

4. **Operational significance:** the study airport's role as a primary gateway for religious pilgrimage traffic gives the findings direct relevance to national aviation safety policy.

While the findings from a single-case study cannot be statistically generalised to the broader population of Saudi aerodromes, the analytical findings—particularly the identification of compounding degradation mechanisms, diminishing rubber removal returns, and the interaction between pavement condition and maintenance feasibility—are expected to be transferable to other aerodromes experiencing similar operational conditions.

1.5. Data Collection and Preparation

1.5.1. Record Identification

All available friction test reports for Runway X/Y during the study period (February 2023 to January 2026) were identified and catalogued. Twelve individual reports were obtained, numbered 1 through 12 by the aerodrome operator. The reports were sorted chronologically by test date, revealing that the report numbering did not follow chronological order (e.g., Report 10 corresponds to the earliest test date of February 7, 2023, while Report 1 corresponds to the most recent test of January 13, 2026). A chronological index was established to facilitate longitudinal analysis.

Air traffic records were identified as three separate Excel workbooks covering non-overlapping time periods. These were merged into a unified monthly time series.

1.5.2. Data Extraction

Friction data were extracted from the PDF test reports using a structured data extraction protocol. For each report, the following data were recorded: test date, report number, environmental conditions (temperature, humidity, wind speed), equipment configuration (tyre type, inflation pressure), and for each of the six passes, the friction coefficient for each runway portion (A, B, C), the pass average, the pass minimum, and the pass maximum. The extracted data were digitised into JSON format to facilitate computational analysis, with each test record containing the complete per-pass results organised by pass identifier (e.g., RWY35-3m, RWY17-6m).

Air traffic data were extracted from the Excel workbooks at the monthly level, recording landing counts and cumulative MTOW mass by runway end.

1.5.3. Data Organisation

The digitised data were organised into three interlinked JSON datasets:

1. **Friction dataset** (`friction\_data\_all\_reports.json`): Contains the complete per-pass results for all 10 unique test dates, organised chronologically, with environmental and equipment metadata.
2. **Air traffic dataset** (`air\_traffic\_data.json`): Contains monthly landing counts and mass data by runway end for all available months, together with the ICAO frequency reference table.
3. **Integrated analysis dataset** (`integrated\_analysis.json`): Links consecutive friction tests by calculating inter-test periods, cumulative landings by runway end, friction changes, and degradation rates.

This linked structure enables direct analysis of the relationships between traffic loading and friction change across each inter-test period.

1.5.4. Data Cleaning

The data cleaning process identified two categories of issues:

Duplicate reports: Reports 2 and 8 were identified as documenting the same friction test (June 19, 2024), and Reports 3 and 4 were identified as documenting the same test (October 21, 2025). In each case, the duplicate pairs contained identical friction values, confirming that they represented the same survey rather than repeated surveys on the same date. The duplicates were merged into single records for the respective dates.

Anomalous values: Friction values exceeding 1.0 were identified in the initial 100–150 metres of multiple test passes. These elevated values are a known artefact of the CFME acceleration zone—the vehicle has not yet reached its target speed of 65 km/h, and the slower measurement speed produces inflated friction readings. These values were retained in the dataset but flagged as acceleration-zone artefacts and excluded from threshold comparisons. Similarly, the ICE percentage indicator, which registered non-zero values (up to 1.27%) in some tests conducted under conditions where ice formation is physically impossible (ambient temperatures of 16–40°C in the study

airport's arid climate), was noted as a software artefact and disregarded in the analysis.

1.5.5. Missing Data Treatment

Air traffic data were unavailable for two periods: November 2024 through April 2025 (6 months) and November 2025 through January 2026 (3 months). To enable the calculation of cumulative traffic between friction tests that span these gaps, missing monthly values were estimated using the arithmetic mean of all available months for the corresponding runway end.

The estimation parameters were:

- Average monthly RWY Y landings: 1,806
- Average monthly RWY X landings: 957
- Average monthly total landings: 2,801
- Average monthly RWY Y mass: approximately 2.91 billion kg

This estimation approach assumes that traffic during the missing months was broadly consistent with the overall study-period average. While this assumption cannot be verified, it is considered reasonable given that the missing periods span a mix of seasonal conditions (including both high-traffic Umrah months and lower-traffic summer months) that would, in aggregate, approximate the annual average. All inter-test periods that incorporate estimated traffic data are flagged in the analysis to ensure transparency regarding data quality.

1.6. Data Analysis Methods

The analytical methodology employs six complementary quantitative approaches, applied sequentially to build understanding from description through pattern identification to relational analysis.

1.6.1. Descriptive Analysis

Descriptive statistics—including means, medians, standard deviations, ranges, and minimum/maximum values—are computed for all key friction variables at multiple levels of aggregation: overall runway average, per-pass average, per-portion average, and per-offset average. Summary statistics are also computed for traffic variables (monthly landings by runway end, cumulative landings between tests). Descriptive

analysis establishes the empirical baseline and provides the context for interpreting subsequent analytical findings.

1.6.2. Trend Analysis

Longitudinal friction trends are analysed by tracking the change in overall average friction across the 10 test dates spanning three years. The trend analysis identifies the direction, magnitude, and rate of friction change over time, with particular attention to transition points where the trend changes character (e.g., acceleration of decline, temporary reversal following rubber removal). The trend is visualised as a time-series plot with the three ICAO thresholds (DOL, MPL, MFL) superimposed as reference lines.

1.6.3. Comparative Analysis

Comparative analysis applied in two dimensions. First, **pre-versus-post rubber removal comparisons** evaluate the effectiveness of each of the three confirmed rubber removal events by calculating the friction change ($\Delta\mu$) from the pre-removal test to the post-removal confirmation test. Successive events are compared to detect the diminishing returns pattern. Second, **lateral offset comparisons** evaluate friction performance across the three measurement offsets (3 m, 6 m, 9 m) to characterise the spatial distribution of rubber contamination across the runway width and identify the critical zone.

1.6.4. Relationship Analysis

The relationship between air traffic loading and friction degradation is analysed by correlating cumulative landings (by runway end) during each inter-test period with the observed friction change. This analysis restricted to periods where no rubber removal occurred, ensuring that the observed friction change reflects degradation rather than maintenance-induced recovery. The analysis examines whether higher cumulative traffic loads produce greater friction decline and whether the relationship is consistent across time or changes as the pavement ages.

1.6.5. Degradation Rate Calculation

For each inter-test period without rubber removal, the degradation rate is calculated as:

$$\text{Degradation Rate } (\mu \text{ per } 1,000 \text{ landings}) = \Delta\mu / (\text{Cumulative RWY Y Landings} / 1,000)$$

where $\Delta\mu$ is the change in overall average friction between consecutive tests and Cumulative RWY Y Landings is the total number of landings on the predominant runway end during the inter-test period. RWY Y landings are used as the denominator because RWY Y receives approximately 65% of all landing traffic and represents the primary driver of rubber accumulation. The degradation rate expressed per 1,000 landings enables comparison across periods of different duration and different traffic intensity, providing a normalised metric of friction sensitivity to traffic loading.

1.6.6. ICAO Compliance Analysis

The ICAO frequency compliance analysis evaluates whether the actual friction testing and rubber removal frequencies at the study airport meet the recommended frequencies prescribed by ICAO guidance material (Doc 9137). Two complementary approaches are employed:

1. **Landing-based analysis:** The average monthly landing count for each runway end is compared against the ICAO reference table to determine the recommended minimum friction survey frequency and minimum rubber removal frequency.
2. **Mass-based analysis:** The annual cumulative mass (in millions of kilograms) for each runway end is compared against the mass-based brackets in the ICAO reference table, which may indicate more frequent maintenance requirements than the landing-based analysis alone.

The actual frequencies observed in the study period are then compared against the ICAO recommendations to identify any compliance gaps.

1.7. Friction Interpretation Framework

The interpretation of friction test results in this study employs the three-tier threshold system specified by ICAO for the ASFT operating at 65 km/h:

Table 3-1: Comparison and Evolution

Threshold Level	Value (μ)	Interpretation	Required Action
Design Friction Level (DOL)	0.82	Target for new/resurfaced pavement	Benchmark for construction quality
Maintenance Planning Level (MPL)	0.60	Friction approaching unacceptable level	Schedule corrective maintenance
Minimum Friction Level (MFL)	0.50	Minimum acceptable operational level	Immediate corrective action + NOTAM

The interpretation framework applies these thresholds at multiple analytical levels. At the **aggregate level**, the overall average friction for each test date is compared against the DOL to assess the general friction condition of the runway. At the **portion level**, the average friction for each runway third is evaluated against the MPL to identify sections requiring maintenance planning. At the **point level**, the minimum recorded friction value in any pass is evaluated against the MFL to identify localised areas of critical concern. This multi-level approach ensures that aggregate metrics—which can mask severe localised deficiencies—do not obscure the presence of safety-critical zones.

1.8. Validity and Reliability

Internal validity is supported by the use of standardised operational data collected under controlled conditions. Friction measurements are produced by a calibrated CFME (a certified ASFT, a certified ASFT vehicle) operating under ICAO-specified conditions (65 km/h test speed, self-wetting water film, standardised tyre), reducing measurement variability and bias. The use of six test passes per survey (three offsets $\times$ two directions) provides spatial triangulation of friction estimates. The structured data extraction protocol ensures consistent handling across all records. The longitudinal design, with 10 measurement points over three years, enables trend confirmation through multiple observations rather than reliance on a single data point.

Reliability is supported by the standardised nature of the CFME measurement process. The a certified ASFT vehicle operates under tightly defined conditions that

minimise measurement variability between tests. Equipment calibration records confirm that the measurement system is maintained within specified tolerances. The consistency of results across the six passes within each test cycle—with systematic variation between offsets reflecting genuine spatial friction differences rather than random measurement error—provides evidence of measurement reliability. The identification of duplicate reports (2/8 and 3/4) and their perfect correspondence provides additional confirmation of data recording reliability.

External validity is inherently limited by the single-case study design. The quantitative relationships identified (e.g., degradation rate per 1,000 landings) are specific to the pavement, climate, traffic mix, and maintenance conditions at the study airport and should not be extrapolated directly to other facilities. However, the qualitative patterns—such as the compounding degradation cycle, the diminishing returns of rubber removal, and the spatial concentration of contamination in the touchdown zone and at the 6-metre lateral offset—are grounded in the physics of rubber deposition and pavement wear and are expected to be broadly transferable. The decision-support framework developed from these findings is designed to be adaptable to other aerodromes through calibration with local data.

To further enhance the technical validity and practical reliability of the study, the research methodology and underlying engineering assumptions were independently reviewed by an industry expert with extensive experience in runway and airside infrastructure operations.

The review specifically examined the friction analysis approach, traffic-based interpretation, and rubber removal practices, as well as the overall applicability of the proposed decision-support framework in real operational environments.

The expert confirmed that the methodological approach and analytical framework are technically sound, operationally relevant, and aligned with current airside maintenance practices. A formal technical review letter is provided in Appendix A.

1.9. Ethical Considerations

This study analyses operational data from an active international airport. Several ethical considerations apply:

- **Data access and confidentiality:** Operational data were accessed with the knowledge and cooperation of the aerodrome operator. The data are used

exclusively for academic research purposes and are presented at a level of detail that supports the analytical objectives while respecting operational confidentiality requirements.

- **Non-interference:** The study is based entirely on retrospective analysis of historical records. No intervention in, or modification of, operational practices was undertaken as part of the research.
- **Academic integrity:** All data presented in the analysis are drawn from the actual operational records. No data have been fabricated, falsified, or selectively omitted to support predetermined conclusions.
- **Safety responsibility:** Findings indicating safety concerns—particularly the identification of friction values below the Minimum Friction Level and the documented inability to perform required maintenance due to pavement deterioration—have been communicated to the relevant operational authorities through proper channels, independent of the academic publication process.

This chapter has described the research methodology employed in this study, including the research design, unit of analysis, data sources, data collection and preparation procedures, analytical methods, and validity and ethical considerations. The following chapter presents the detailed analysis and findings of the case study.

Chapter 4 ANALYSIS AND CASE STUDY

2.1.Introduction

This chapter presents the comprehensive analysis of friction test data, air traffic data, and rubber removal records from Runway X/Y at a major Saudi international airport (hereinafter referred to as "the study airport"), the study city, Saudi Arabia. The analysis follows the methodological framework established in Chapter 3, progressing systematically from descriptive characterisation through longitudinal trend analysis, spatial distribution analysis, traffic analysis, ICAO compliance assessment, integrated traffic-friction analysis, and rubber removal effectiveness evaluation, culminating in the identification of a compounding pavement degradation cycle that represents the study's core empirical contribution.

The dataset comprises 10 unique friction surveys spanning approximately three years (February 7, 2023, to January 13, 2026), 28 months of air traffic data (January 2023 to October 2025, with gaps estimated), and three confirmed rubber removal events plus one prevented event. This longitudinal depth enables the identification of progressive patterns—accelerating degradation, diminishing maintenance returns, and eventual maintenance infeasibility—that would be invisible in a cross-sectional analysis of a single test.

The chapter is structured to build analytical understanding cumulatively. Sections 4.2 through 4.3 establish the physical and empirical context. Sections 4.4 through 4.6 analyse the three primary data streams independently (friction trends, lateral offsets, and air traffic). Sections 4.7 through 4.9 integrate these streams to reveal the relationships between traffic, friction, and maintenance. Section 4.10 presents the compounding degradation finding. Section 4.11 summarises the key findings.

2.2. Airport and Runway Characteristics

the study airport (IATA code withheld, ICAO code withheld for confidentiality for confidentiality) is located approximately near the city centre of the study city in the Saudi Arabia, at an elevation of approximately elevated above mean sea level. The airport is operated by the airport operating company under a Build-Transfer-Operate (BTO) concession agreement and serves as a primary gateway for religious pilgrimage traffic to the holy sites and the holy sites of the study city. In 2024, the airport handled approximately over 10 million passengers, making it the one of the

busiest airports in the Kingdom of Saudi Arabia and one of the most operationally significant aerodromes in the GACA regulatory domain.

The airport operates two runways in a main/standby configuration. Runway X/Y, the subject of this study, is the main operational runway handling the vast majority of commercial operations. Runway A/B (3,050 m x 45 m) serves as the standby runway and is activated primarily when Runway X/Y is unavailable due to maintenance or when operational conditions (crosswind, traffic volume) warrant its use. Traffic data confirm that RWY A and RWY B together receive fewer than 1% of total landing operations, underscoring the near-total concentration of traffic and rubber accumulation on the study runway.

Table 4-1 Runway X/Y Technical Specifications

Parameter	Specification
Designation	RWY X/Y
Length	4,335 m
Width	60 m
Orientation	170° / 350°
Surface — First 250 m (each end)	Concrete (PCR 910/R/A/W/T)
Surface — Remainder	Asphalt (PCR 850/F/A/X/T)
Stopway	120 m at each end
Role	Main operational runway
Friction test equipment	a certified ASFT (withheld for confidentiality), 65 km/h

The mixed surface composition—concrete for the first 250 metres from each threshold transitioning to asphalt for the remainder—is significant for friction management. The concrete sections, which coincide with the initial touchdown area for short-landing aircraft, are more resistant to rubber accumulation and high-pressure water removal. The asphalt sections, which encompass the primary touchdown zone

(typically 300–600 metres from the threshold) and the runway mid-section, are more susceptible both to rubber embedment and to damage from the rubber removal process. This differential susceptibility creates asymmetric deterioration profiles along the runway length.

the study airport's climate is characterised by extreme heat (summer temperatures regularly exceeding 45°C), very low humidity (typically 10–15%), minimal rainfall, and strong solar radiation. These conditions accelerate oxidative hardening of the asphalt binder, making the pavement surface progressively more brittle and more vulnerable to damage from both traffic loading and maintenance operations. The climatic context is directly relevant to the compounding degradation findings presented in Section 4.10.

2.3. Friction Test Results Overview

Table 4.2 presents the summary results for all 10 unique friction tests conducted on Runway X/Y during the study period. Each row represents a complete friction survey consisting of six test passes.

Table 4-2 Summary of All Friction Test Results (February 2023 – January 2026)

#	Date	Temp (°C)	Humidity (%)	Wind (km/h)	Tyre / Pressure	Passes	Overall Avg (μ)	Min (μ)	Max (μ)	Note
1	2023-02-07	16	13	30	T49 / 7.0 bar	6	0.82	0.34	1.15	Baseline test
2	2023-03-03	32	10	35	T49 / 7.0 bar	6	0.85	0.46	1.05	Post rubber removal (+0.03)
3	2023-08-06	40	13	11	ASTM / 7.0 bar	6	0.79	0.39	1.15	Tyre change; degradation
4	2023-09-23	34	13	10	ASTM / 7.0 bar	6	0.79	0.44	1.09	Stable
5	2024-01-30	16	13	19	ASTM / 2.1 bar	6	0.89	0.60	1.09	Post rubber removal

										(+0.10); highest recorded
6	2024-06-19	40	13	18	ASTM / 2.1 bar	6	0.72	0.38	1.13	Severe drop (−0.17) in 5 months
7	2025-03-10	30	12	18	ASTM / 2.1 bar	6	0.70	0.28	1.02	Critical low; min below MFL
8	2025-04-27	40	11	18	ASTM / 2.1 bar	6	0.76	0.53	1.07	Post rubber removal (+0.06); did not reach DOL
9	2025-10-21	33	10	16	ASTM / 2.1 bar	6	0.71	0.33	1.00	Declining; rubber removal prevented
10	2026-01-13	18	16	19	ASTM / 2.1 bar	6	0.69	0.27	1.13	Lowest average; min far below MFL

Source: the study airport friction test reports, Reports 1–12 (withheld for confidentiality).

Several observations emerge from this summary:

Declining trajectory: The overall average friction ranged from a high of 0.89 μ (January 2024, post rubber removal) to a low of 0.69 μ (January 2026), representing a 22.5% decline in the best achievable friction over the two-year period. Even excluding post-removal peaks, the pre-removal friction declined steadily: 0.82 μ (February 2023), 0.79 μ (August and September 2023), 0.72 μ (June 2024), 0.70 μ (March 2025), 0.71 μ (October 2025), and 0.69 μ (January 2026).

Worsening minimum values: The minimum recorded friction value declined from 0.60 μ at best (January 2024, post rubber removal) to 0.27 μ at worst (January 2026)—

a value that is 46% below the Minimum Friction Level of 0.50μ , representing a severe safety concern in localised zones. Even the post-removal minimum values worsened: 0.46μ (March 2023), 0.60μ (January 2024), and 0.53μ (April 2025). The January 2024 result of 0.60μ is notable as it equals the MPL exactly, indicating that even immediately after rubber removal, certain runway zones were at the maintenance planning threshold.

Environmental conditions: Tests were conducted across a wide range of temperatures ($16\text{--}40^{\circ}\text{C}$), with humidity consistently low ($10\text{--}16\%$) and wind speeds varying from 10 to 35 km/h. The low humidity is characteristic of the study airport's arid climate and ensures that tests were conducted under dry conditions as required by ICAO methodology. Temperature variation is a potential confound—higher temperatures may soften existing rubber deposits and affect measured friction—but the longitudinal trend persists when controlling for temperature: the two tests conducted at $16\text{--}18^{\circ}\text{C}$ (February 2023 at 0.82μ and January 2026 at 0.69μ) show a decline of 0.13μ under comparable conditions.

ICE percentage artefact: The ICE percentage indicator shows a rising trend in the later tests (0.71% in October 2025, 1.27% in January 2026). Given that ice formation is physically impossible under the study city's climatic conditions (minimum test temperature 16°C), these readings represent a measurement artefact likely triggered by extremely low friction values in certain runway segments that the software misclassifies as ice contamination. The rising ICE percentage thus serves as an indirect indicator of worsening friction conditions.

Figure 4.1 (chart_01_longitudinal_trend.png) illustrates the longitudinal trend of overall average friction across all 10 test dates, with the DOL, MPL, and MFL thresholds superimposed. Figure 4.7 (chart_07_friction_range.png) illustrates the range between minimum and maximum friction values at each test date, revealing the widening dispersion that characterises progressive degradation.

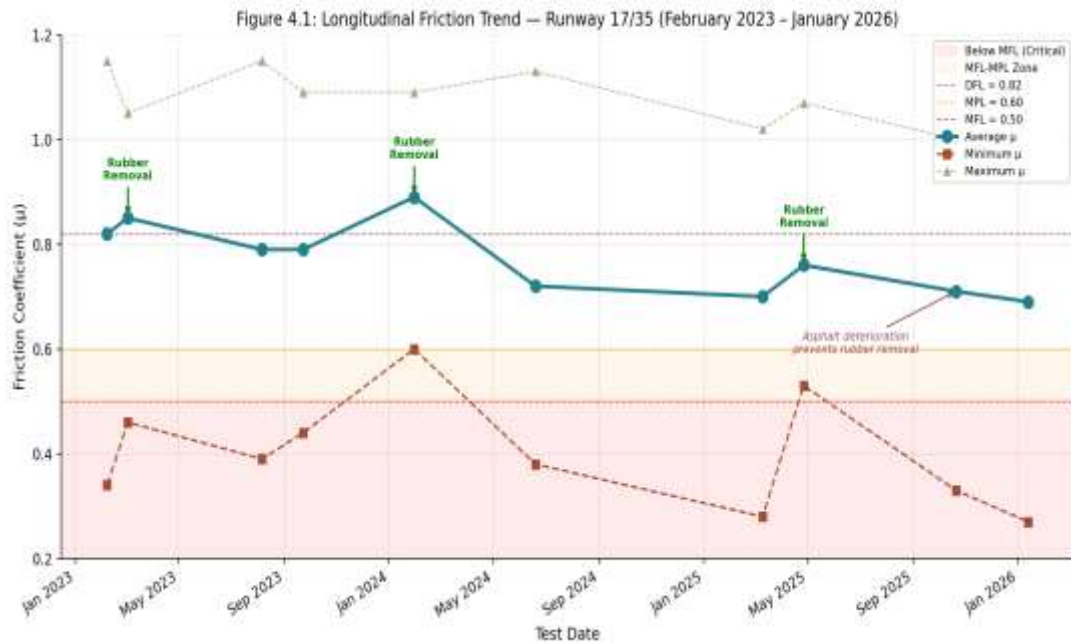


Figure 4-1 Longitudinal Friction trend

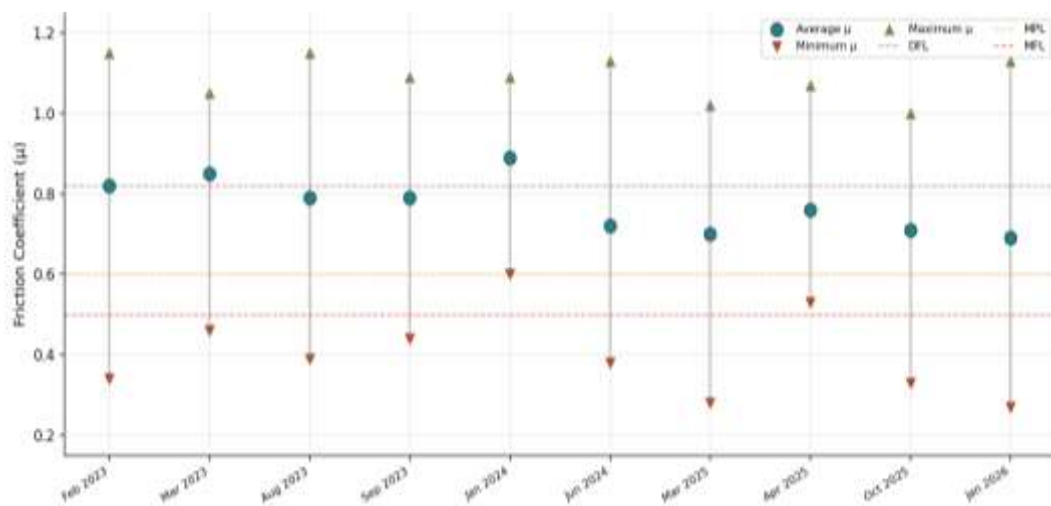


Figure 4-2 Friction range

2.4. Longitudinal Friction Trend Analysis

The longitudinal analysis of friction performance over the three-year study period reveals a clear and statistically significant declining trend punctuated by temporary reversals following rubber removal events.

2.4.1. Summary Statistics

Across all 10 test dates, the descriptive statistics for the overall average friction coefficient are:

- **Mean:** 0.77μ

- **Median:** 0.78μ (midpoint between 0.79 and 0.76)
- **Standard deviation:** 0.066μ
- **Range:** 0.20μ (from 0.69 to 0.89)
- **Coefficient of variation:** 8.6%

The mean of 0.77μ falls below the DOL of 0.82μ , indicating that the runway's average condition over the study period did not meet the design target. The standard deviation of 0.066μ and coefficient of variation of 8.6% indicate moderate variability, driven primarily by the contrast between post-removal peaks and pre-removal troughs.

2.4.2. Three-Phase Degradation Pattern

The longitudinal data reveal three distinct phases in the pavement's friction lifecycle, as illustrated in Figure 4.1 (chart_01_longitudinal_trend.png):

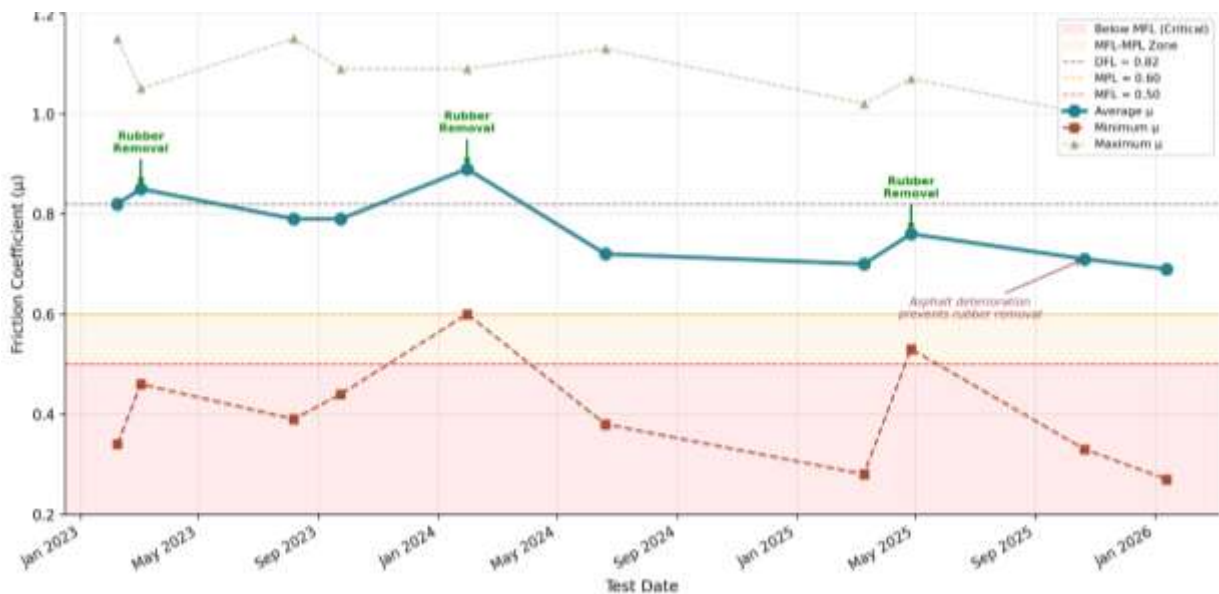


Figure 4-3 Longitudinal Friction Evolution

Phase 1: Healthy Pavement (February 2023 – January 2024). During this initial phase, friction values ranged from 0.79μ to 0.89μ . Two rubber removal events occurred, and both successfully restored friction to or above the DOL. The first event (February–March 2023) raised friction from 0.82μ to 0.85μ , and the second event (September 2023–January 2024) raised friction from 0.79μ to 0.89μ —the highest

value recorded in the entire study. Degradation between removals was moderate, with the rate calculated at -0.006μ per 1,000 RWY Y landings during the March–August 2023 period. The pavement was responsive to maintenance, and the rubber removal process effectively restored friction to near-design levels.

Phase 2: Accelerating Degradation (January 2024 – March 2025). This phase is characterised by a dramatic acceleration in friction decline. Following the January 2024 post-removal peak of 0.89μ , friction dropped precipitously to 0.72μ by June 2024—a decline of 0.17μ in just five months. This represents a degradation rate of -0.014μ per 1,000 RWY Y landings, which is more than double the Phase 1 rate. Friction continued to decline to 0.70μ by March 2025, at which point the minimum recorded value of 0.28μ was well below the MFL. The accelerated degradation rate during this phase suggests that the pavement's intrinsic friction capacity had begun to diminish, causing rubber to accumulate more rapidly on an increasingly compromised surface.

Phase 3: Structural Degradation (April 2025 – January 2026). The third phase marks the transition from a friction management problem to a pavement condition crisis. The March 2025 rubber removal event restored friction only to 0.76μ —far below the 0.85 – 0.89μ achieved in earlier removals, confirming the diminishing returns pattern. More critically, when friction again declined to 0.71μ by October 2025 and further to 0.69μ by January 2026, rubber removal could not be performed because the asphalt pavement had deteriorated to the point where the application of high-pressure water would cause further structural damage. The runway entered a compounding degradation cycle in which pavement deterioration prevented the maintenance that would arrest friction decline, causing further friction loss that could not be remediated.

2.4.3. Transition Points

The data reveal two critical transition points. The first occurs between January 2024 and June 2024, where the degradation rate more than doubled from the Phase 1 baseline. This transition suggests that the cumulative effects of traffic loading and previous rubber removal cycles had begun to exceed the pavement's capacity to sustain its friction characteristics. The second transition occurs between March and October 2025, where the inability to perform rubber removal marked the onset of a

qualitatively different operational state—one in which conventional maintenance tools were no longer available, and friction decline became effectively uncontrollable without pavement rehabilitation.

2.5. Lateral Offset Analysis

The availability of friction data at three lateral offsets (3 m, 6 m, and 9 m from the runway centreline) enables characterisation of the spatial distribution of rubber contamination across the runway width. This analysis provides direct evidence of where rubber accumulates most heavily and, consequently, where friction is most degraded.

Table 4-3 Average Friction by Lateral Offset and Direction — All 10 Tests

Test Date	RWY35-3m	RWY35-6m	RWY35-9m	RWY17-3m	RWY17-6m	RWY17-9m
2023-02-07	0.83	0.72	0.92	0.84	0.71	0.91
2023-03-03	0.87	0.83	0.87	0.81	0.88	0.83
2023-08-06	0.79	0.71	0.85	0.85	0.74	0.82
2023-09-23	0.78	0.71	0.84	0.78	0.73	0.88
2024-01-30	0.85	0.85	0.93	0.91	0.87	0.95
2024-06-19	0.71	0.66	0.72	0.75	0.71	0.79
2025-03-10	0.68	0.63	0.75	0.71	0.67	0.77
2025-04-27	0.72	0.69	0.84	0.76	0.73	0.81
2025-10-21	0.74	0.69	0.65	0.67	0.68	0.85
2026-01-13	0.64	0.61	0.73	0.69	0.66	0.80
Mean	0.76	0.71	0.81	0.78	0.74	0.84

Source: the study airport friction test reports, Reports 1–12 (withheld for confidentiality).

2.5.1. The 6-Metre Critical Zone

The most consistent and analytically significant finding from the lateral offset analysis that the **6-metre offset consistently records the lowest friction** across almost all tests and both runway directions. Across all 10 tests:

- The mean friction at 6 m from centreline (both directions combined) is 0.73μ —the lowest of the three offsets.
- The mean friction at 3 m from centreline is 0.77μ —moderately higher.
- The mean friction at 9 m from centreline is 0.83μ —approaching the DOL.

The differential between the 6-metre and 9-metre offsets (0.10μ , or approximately 12%) is substantial and statistically consistent across test dates. This pattern is illustrated in Figure 4.6 (chart_06_offset_comparison.png) and the critical zone detail in Figure 4.9 (chart_11_critical_zone_6m.png).

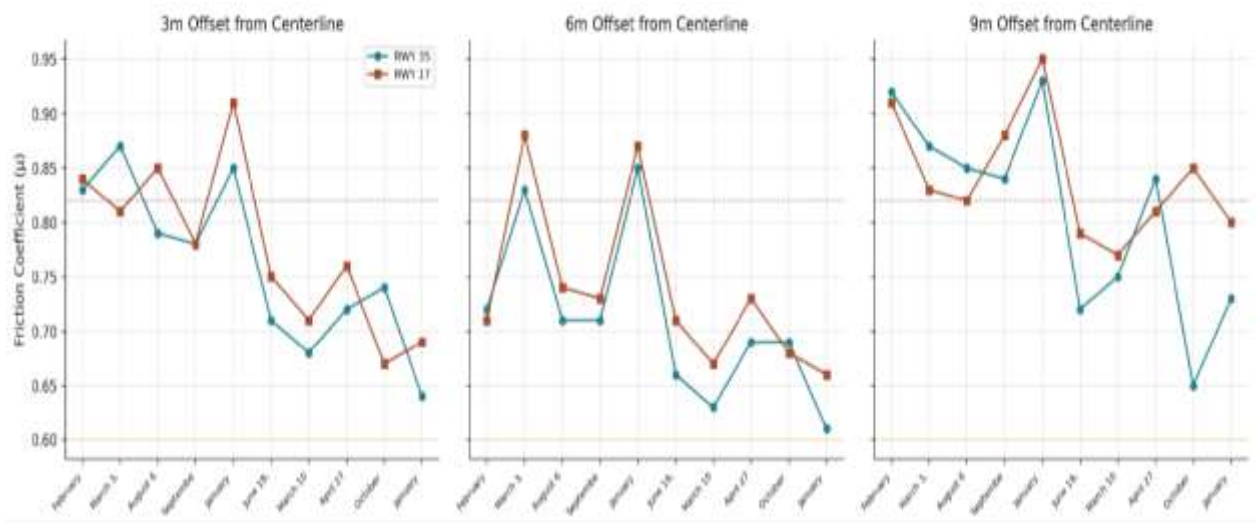


Figure 4-4 Offset comparison

The finding that the 6-metre offset—rather than the 3-metre offset closest to the centreline—shows the lowest friction is physically significant. It indicates that the primary rubber deposition band is centred not on the runway centreline but at approximately 5–7 metres from the centreline, corresponding to the typical lateral position of the main landing gear of the predominant aircraft types. For narrow-body aircraft such as the Airbus A320 family and Boeing 737 series, which constitute the majority of operations at the study airport, the main landing gear track width places

the outboard tyres approximately 4–7 metres from the centreline. The 6-metre offset measurement thus captures the zone of maximum rubber accumulation, providing direct evidence that rubber contamination is **spatially concentrated along the main gear tracks**.

2.5.2. Directional Patterns

Comparing the two runway directions reveals that RWY Y passes consistently show lower friction than corresponding RWY X passes at the same lateral offset. Across all 10 tests, the mean friction for RWY Y passes is 0.76μ compared to 0.79μ for RWY X passes—a difference of 0.03μ . This directional asymmetry is consistent with the traffic distribution data presented in Section 4.6, which show that RWY Y receives approximately 65% of all landing operations, concentrating rubber deposition at the RWY Y touchdown zone.

2.5.3. Temporal Evolution of Lateral Patterns

The lateral offset pattern intensifies over time. In the early tests (2023), the differential between the 6-metre and 9-metre offsets was approximately $0.10\text{--}0.20\mu$, reflecting a clear distinction between the rubber-contaminated gear track zone and the cleaner outer runway. By the final tests (2025–2026), this differential had narrowed in some cases—not because the 6-metre offset improved, but because the 9-metre offset also began to degrade.

The January 2024 post-removal test (Test 5) provides the clearest snapshot of the lateral pattern under ideal conditions. After rubber removal, the 6-metre offset averages (0.85μ for RWY Y, 0.87μ for RWY X) were close to the 3-metre values (0.85μ and 0.91μ respectively), and the 9-metre offset reached the highest values in the dataset (0.93μ and 0.95μ). This confirms that when rubber is removed, the lateral gradient flattens substantially, demonstrating that the differential is driven by rubber contamination rather than by intrinsic pavement friction differences across the runway width.

The October 2025 test (Test 9) is particularly notable: the RWY35-9m average dropped to 0.65μ , substantially below its historical range and below the 3-metre offset (0.74μ). This anomalous reversal may reflect the onset of pavement-wide surface deterioration that extends beyond the rubber contamination zone, consistent with the structural degradation phase described in Section 4.4.2. The reversal did not persist in

the RWY X direction (where the 9-metre offset remained the highest at 0.85µ), suggesting that the pavement deterioration may be localised to specific sections of the RWY Y outer lane, possibly reflecting differential water drainage or surface course aging patterns.

The progressive convergence of the three offset values in later tests has an important practical implication: as the pavement degrades structurally, the spatial intelligence provided by offset-differentiated testing becomes less useful for targeting rubber removal, because the problem transitions from spatially concentrated contamination to diffuse pavement failure. This transition signals the shift from a friction management problem (addressable through rubber removal) to a pavement management problem (requiring rehabilitation or resurfacing).

2.6. Air Traffic Analysis

Air traffic data for Runway X/Y were available for 28 months across the study period. Table 4.4 presents the complete monthly landing data for the study runway (RWY X and RWY Y only; RWY A/B landings are excluded as they do not affect the study runway's friction).

Table 4-4 Monthly Landings on Runway X/Y (RWY X and RWY Y)

Month	RWY X	RWY Y	Total X/Y	RWY Y Share
2023-01	790	1,613	2,403	67.1%
2023-02	774	1,652	2,426	68.1%
2023-03	1,255	1,292	2,547	50.7%
2023-04	1,109	1,194	2,303	51.8%
2023-05	1,079	1,290	2,369	54.5%
2023-06	709	2,130	2,839	75.0%
2023-07	937	2,527	3,464	73.0%
2023-08	514	1,528	2,042	74.8%
2023-09	530	1,300	1,830	71.0%

2023-10	1,099	1,322	2,421	54.6%
2023-11	1,072	1,527	2,599	58.8%
2023-12	1,289	1,550	2,839	54.6%
2024-01	1,042	2,152	3,194	67.4%
2024-02	985	2,250	3,235	69.6%
2024-03	1,229	2,039	3,268	62.4%
2024-04	1,010	1,640	2,650	61.9%
2024-05	1,680	1,868	3,548	52.6%
2024-06	819	2,248	3,067	73.3%
2024-07	955	2,280	3,235	70.5%
2024-08	879	1,534	2,413	63.6%
2024-09	444	1,998	2,442	81.8%
2024-10	621	2,038	2,659	76.6%
2025-05	1,680	1,868	3,548	52.6%
2025-06	1,040	1,804	2,844	63.4%
2025-07	638	2,220	2,858	77.7%
2025-08	552	1,950	2,502	77.9%
2025-09	864	1,946	2,810	69.3%
2025-10	1,191	1,800	2,991	60.2%

Source: the study airport air traffic records (2023–2025). RWY A/B landings excluded.

2.6.1. RWY Y Predominance

The traffic data unequivocally establish RWY Y as the predominant landing direction. Across all 28 available months, RWY Y accounts for an average of approximately 65% of all landings on Runway X/Y, with a monthly average of 1,806 landings compared to 957 for RWY X. The RWY Y share ranges from a low of 50.7% (March 2023) to a high of 81.8% (September 2024), indicating that while RWY Y consistently receives the majority of traffic, the degree of asymmetry varies seasonally with prevailing wind patterns.

This traffic asymmetry has direct implications for friction management. The RWY Y touchdown zone receives approximately two-thirds of all rubber deposition, creating a higher maintenance demand at that end. The friction data confirm this expectation: RWY Y passes consistently show lower friction than RWY X passes, as documented in Section 4.5.2. As illustrated in Figure 4.3 (chart_03_monthly_traffic.png), the traffic distribution is not uniform throughout the year.

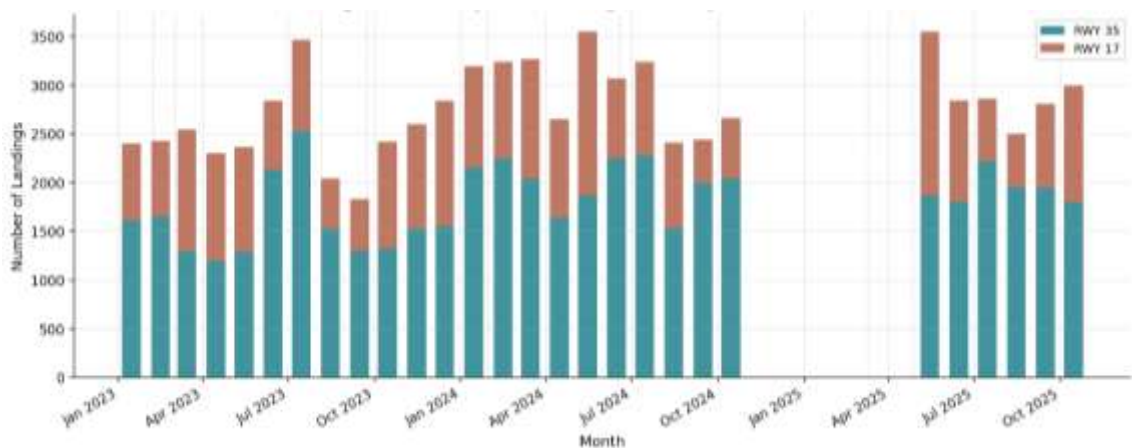


Figure 4-5 Monthly traffic

2.6.2. Seasonal Patterns

The monthly traffic data exhibit clear seasonal patterns driven by the Islamic pilgrimage calendar and general tourism demand, as illustrated in Figure 4.8 (chart_09_seasonality.png):

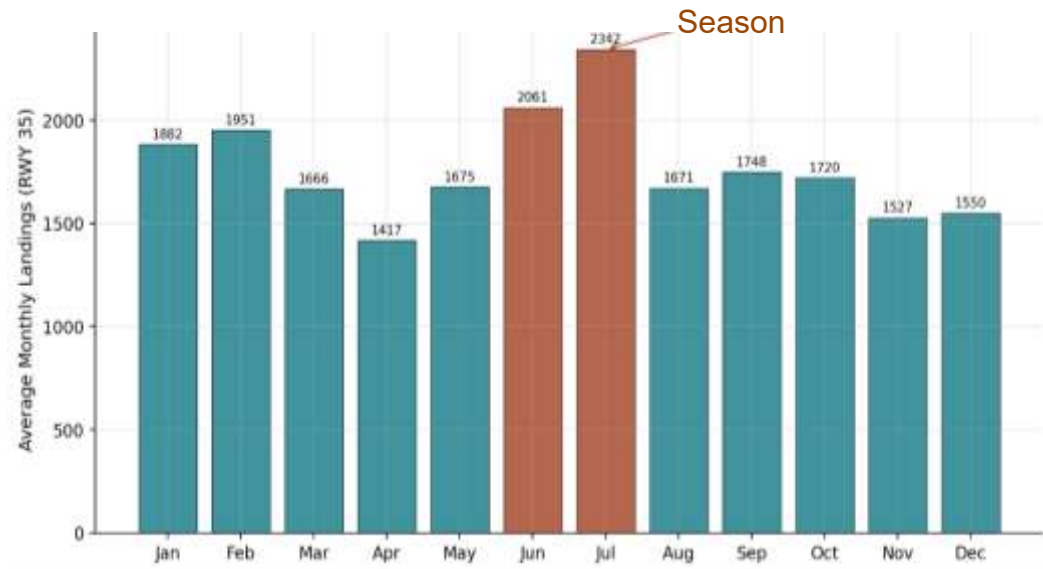


Figure 4-6 Seasonality

- **Hajj season (June–July):** The highest traffic volumes are recorded during the Hajj pilgrimage period. RWY Y landings peak at 2,527 in July 2023 and 2,280 in July 2024. The Hajj traffic surge increases both the total landing count and the RWY Y share (typically exceeding 70%), as prevailing summer winds favour the RWY Y direction.
- **Umrah high season (October–March):** Elevated traffic is observed during the Umrah season, with monthly totals on Runway X/Y typically ranging from 2,400 to 3,300. The extended duration of elevated traffic during Umrah season contributes significantly to cumulative rubber accumulation between maintenance events.
- **Transition and lower-traffic periods (August–September):** Following the Hajj peak, traffic moderates as the extreme summer heat reduces non-pilgrimage travel. RWY X landings decrease during these months as southerly winds diminish.

2.6.3. Year-over-Year Traffic Growth

Comparing the available 2023 and 2024 data reveals modest but consistent traffic growth. The average monthly total landings on Runway X/Y increased from

approximately 2,590 in 2023 to approximately 2,970 in 2024—a year-over-year increase of approximately 15%. This growth is consistent with the broader expansion of Saudi aviation under the Vision 2030 strategic plan and increases the rate of rubber accumulation and pavement loading on the study runway.

Notably, the traffic growth is not uniformly distributed across runway ends. RWY Y landings increased disproportionately, with the average monthly RWY Y count rising from approximately 1,660 in 2023 to approximately 2,005 in 2024 (a 21% increase), while RWY X landings grew more modestly from approximately 930 to 965 (4%). This divergence increases the already asymmetric rubber deposition pattern, concentrating additional wear at the RWY Y touchdown zone and further amplifying the maintenance demand at that end. The growth trend implies that if current patterns continue, the time between maintenance triggers will shorten progressively, compounding the challenges identified in the degradation analysis.

2.6.4. Missing Data Periods

Air traffic data were unavailable for November 2024 through April 2025 and November 2025 through January 2026. These gaps were addressed by substituting the overall monthly averages (RWY Y: 1,806; RWY X: 957) as described in Section 3.5.5. The estimated periods are flagged in all subsequent analyses. While the estimation introduces uncertainty, the alternative—excluding the corresponding friction test periods from analysis—would eliminate critical data points, including the March 2025 pre-removal test and the January 2026 final test, that are essential to the study's core findings.

2.7. ICAO Frequency Compliance Analysis

The ICAO Doc 9137 (Airport Services Manual, Part 2) provides recommended minimum frequencies for both friction surveys and rubber removal, calibrated to traffic intensity as measured by monthly landings and annual mass. Table 4.5 reproduces the relevant ICAO reference table.

Table 4-5 ICAO Recommended Minimum Frequencies for Friction Testing and Rubber Removal

Monthly Landings (from)	Monthly Landings (to)	Annual Landings	Annual Mass from (M kg)	Annual Mass to (Mkg)	Min Friction Survey	Min Rubber Removal
0	450	13,500	0	477	Yearly	Every 2 Years
480	900	27,000	448	838	6 Months	Yearly
930	2,700	81,000	839	2,404	3 Months	Semi-Annual
2,730	4,500	135,000	2,405	3,969	Monthly	Every 4 Months
4,530	6,300	189,000	3,970	5,535	Every 2 Weeks	Every 3 Months
6,300+	—	—	5,535+	—	Weekly	Every 2 Months

Source: ICAO Doc 9137, Airport Services Manual, Part 2 (ICAO, 2015).

2.7.1. Landing-Based Assessment

The average monthly landing count for RWY Y is approximately 1,806, and for RWY X approximately 957. Both values fall within the 930–2,700 monthly landings bracket. Accordingly, the ICAO landing-based recommendations for Runway X/Y are:

- **Minimum friction survey frequency:** Every 3 months
- **Minimum rubber removal frequency:** Semi-annually (every 6 months)

2.7.2. Mass-Based Assessment

The annual cumulative mass for RWY Y is estimated at approximately 2.9 billion kilograms (2,900 Mkg) based on the monthly average mass of approximately 2.91 billion kg extrapolated over 12 months. This value falls within the 2,405–3,969 Mkg bracket. The mass-based ICAO recommendations are therefore:

- **Minimum friction survey frequency:** Monthly
- **Minimum rubber removal frequency:** Every 4 months

The mass-based analysis yields **more stringent** requirements than the landing-based analysis. This occurs because the aircraft fleet mix at the study airport includes a significant proportion of wide-body and heavy aircraft operating pilgrimage charter flights, whose higher MTOW drives the cumulative mass into a higher bracket than the landing count alone would suggest.

4.7.3 Actual Practice vs. ICAO Recommendations

Table 4-6 Required vs. Actual Friction Management Frequencies at the study airport

Activity	ICAO (Landing-Based)	ICAO (Mass-Based)	Actual Practice (Study Period)
Friction survey	Every 3 months	Monthly	Irregular; avg ~3.4 months between tests
Rubber removal	Semi-annually	Every 4 months	~3 events in 36 months (avg ~12 months)

The comparison reveals a significant compliance gap, particularly for rubber removal. While friction surveys were conducted at an average interval of approximately 3.4 months—broadly consistent with the landing-based recommendation of quarterly testing—the actual rubber removal frequency of approximately once per year falls far short of both the semi-annual (landing-based) and quadrimestrial (mass-based) ICAO recommendations.

This gap has direct consequences for friction performance. The extended intervals between rubber removal events allow rubber to accumulate to levels that require more aggressive removal when maintenance is eventually performed, contributing to the compounding degradation cycle identified in Section 4.10. The mass-based analysis, which recommends rubber removal every four months, suggests that the study airport should perform approximately three rubber removal operations per year—triple the actual frequency observed during the study period.

The discrepancy between landing-based and mass-based recommendations is itself analytically significant. It indicates that the aircraft fleet mix at the study airport—which includes a substantial proportion of wide-body aircraft operating pilgrimage charter flights with high MTOW—generates a rubber deposition burden per landing that exceeds the industry average assumed in the landing-count brackets. This finding supports the use of mass-based (rather than purely count-based) metrics in determining maintenance frequencies for airports with atypical fleet compositions, a recommendation developed further in Chapter 5.

The irregular spacing of actual friction surveys during the study period also warrants comment. The 10 tests were not evenly distributed: intervals ranged from 24 days (February to March 2023) to 264 days (June 2024 to March 2025). The longest gaps coincide with the periods of most severe friction decline, meaning that the most critical degradation was occurring during periods of least monitoring. A more systematic quarterly testing regime would have detected the accelerating degradation earlier and potentially triggered earlier intervention.

2.8. Integrated Traffic-Friction Analysis

The integration of traffic data with friction test results enables the analysis of the relationship between cumulative traffic loading and friction degradation. Table 4.7 presents the complete inter-test period analysis, linking each consecutive pair of tests with the intervening traffic volume and the observed friction change.

Table 4-7 Inter-Test Period Analysis — Traffic Load and Friction Change

Period	Days	Cum. RWY Y Landings	Cum. RWY X Landings	Cum. Total	μ Before	μ After	Δμ	Rubber Removal	Deg. Rate (μ/1000 ldg)
Feb 7 → Mar 3, 2023	24	2,944	2,029	5,168	0.82	0.85	+0.03	YES	—
Mar 3 → Aug 6, 2023	156	9,961	5,603	15,786	0.85	0.79	−0.06	NO	−0.0060
Aug 6 → Sep 23, 2023	48	2,828	1,044	4,139	0.79	0.79	0.00	NO	0.0000

Sep 23, 2023 → Jan 30, 2024	129	7,851	5,032	13,171	0.79	0.89	+0.10	YES	—
Jan 30 → Jun 19, 2024	141	12,197	6,765	19,290	0.89	0.72	−0.17	NO	−0.0139
Jun 19, 2024 → Mar 10, 2025	264	19,123	8,498	28,019	0.72	0.70	−0.02	NO	−0.0010
Mar 10 → Apr 27, 2025	48	3,610	1,912	5,602	0.70	0.76	+0.06	YES	—
Apr 27 → Oct 21, 2025	177	13,393	6,921	20,547	0.76	0.71	−0.05	NO	−0.0037
Oct 21, 2025 → Jan 13, 2026	84	7,215	4,059	11,403	0.71	0.69	−0.02	NO	−0.0028

Source: Integrated analysis of the study airport friction and traffic data. Periods spanning missing traffic data are marked; estimated values used.

Figure 4.4 (chart_04_traffic_vs_degradation.png) plots cumulative RWY Y landings against friction change for each non-removal period, and Figure 4.5 (chart_05_degradation_rates.png) tracks the degradation rate across successive periods.

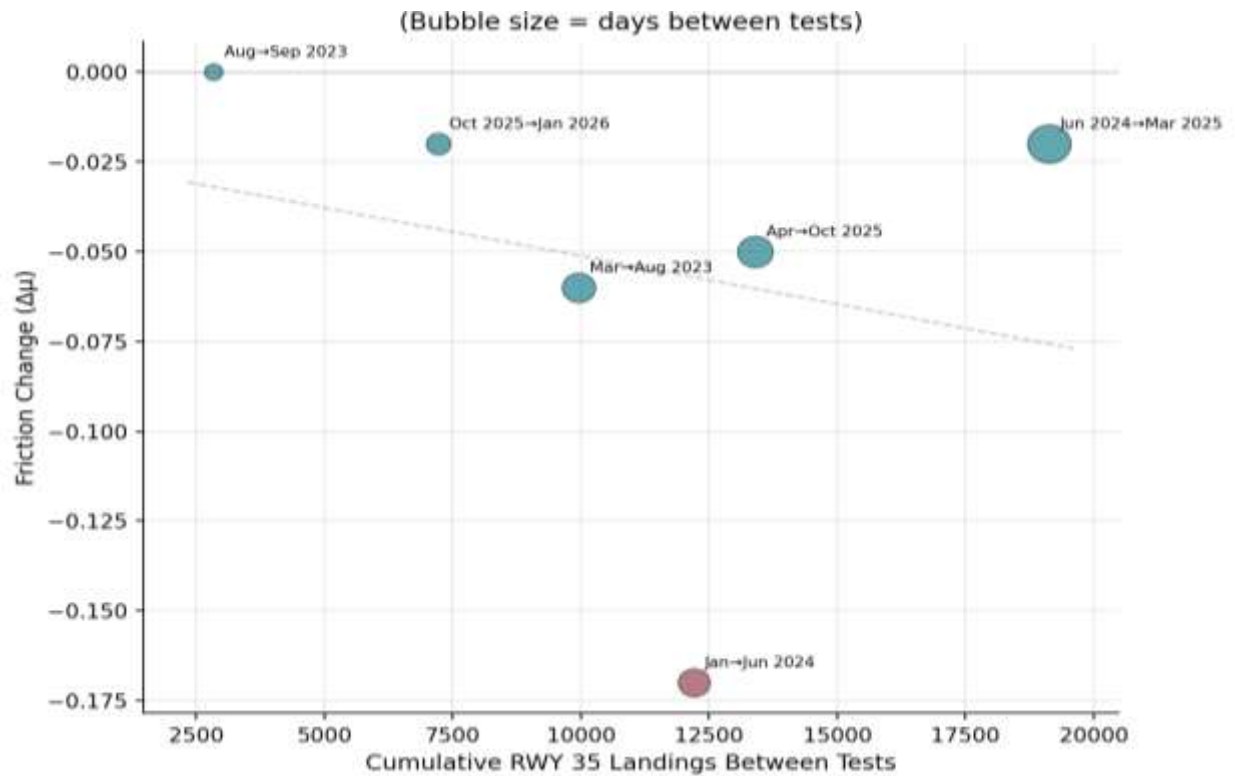


Figure 4-8 Cumulative traffic load vs Friction Degradation

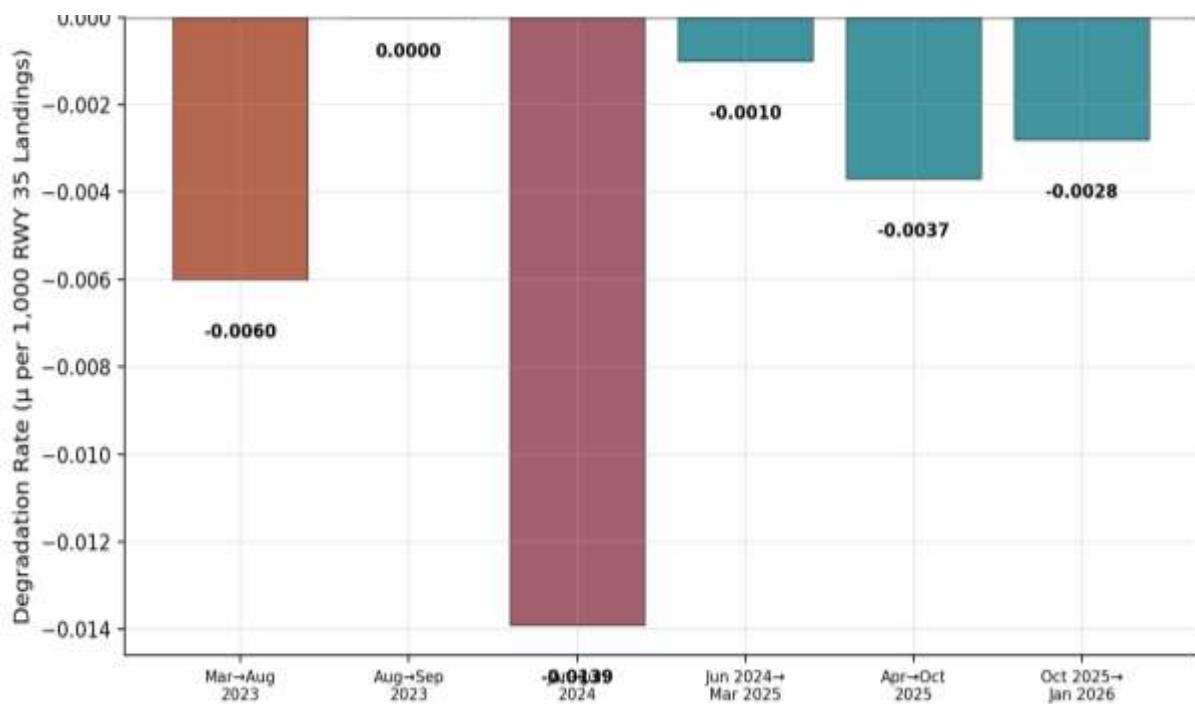


Figure 4-7 Friction degradation rate per 1,000 Landings – Temporal Evolution

2.8.1. Period-by-Period Analysis

Period 1 (Mar 3 – Aug 6, 2023): Over 156 days and 9,961 RWY Y landings, friction declined from 0.85μ to 0.79μ ($\Delta = -0.06$). The degradation rate of -0.006μ per 1,000 landings represents the baseline rate during the healthy pavement phase. This moderate rate reflects a pavement surface that, having just undergone rubber removal, was in good condition and degraded proportionally to traffic loading.

Period 2 (Aug 6 – Sep 23, 2023): Over 48 days and 2,828 RWY Y landings, friction remained stable at 0.79μ ($\Delta = 0.00$). The apparent zero degradation over this short period likely reflects a combination of the relatively low traffic volume (coinciding with the post-Hajj low season) and the measurement resolution of the test equipment. The pavement was degrading, but at a rate too slow to produce a detectable change over the limited interval.

Period 3 (Jan 30 – Jun 19, 2024): This period is the most analytically significant for understanding degradation dynamics. Over 141 days and 12,197 RWY Y landings, friction plummeted from 0.89μ to 0.72μ ($\Delta = -0.17$)—the largest single-period decline in the entire dataset. The degradation rate of **-0.014μ per 1,000 landings** is more than double the Phase 1 rate of -0.006μ . This acceleration cannot be attributed solely to the higher traffic volume; the normalised rate (per 1,000 landings) explicitly controls for traffic intensity. Instead, the accelerated rate indicates that the pavement's intrinsic resistance to friction degradation had diminished—the surface was accumulating rubber more rapidly per unit of traffic than it had previously, suggesting incipient pavement deterioration.

Period 4 (Jun 19, 2024 – Mar 10, 2025): Over 264 days and an estimated 19,123 RWY Y landings, friction declined only marginally from 0.72μ to 0.70μ ($\Delta = -0.02$), yielding an apparent degradation rate of -0.001μ per 1,000 landings. This apparently low rate is potentially misleading. With friction already at 0.72μ —well below the DOL—the pavement may have been approaching a friction floor below which degradation occurs at a reduced rate because the surface is already heavily saturated with rubber. Additionally, five of the ten months in this period use estimated traffic data, introducing uncertainty into the cumulative landing count.

Period 5 (Apr 27 – Oct 21, 2025): Over 177 days and 13,393 RWY Y landings, friction declined from 0.76μ to 0.71μ ($\Delta = -0.05$), yielding a rate of -0.004μ per

1,000 landings. This period follows the third rubber removal event and represents the post-removal degradation cycle in the structural degradation phase.

Period 6 (Oct 21, 2025 – Jan 13, 2026): Over 84 days and an estimated 7,215 RWY Y landings, friction declined from 0.71μ to 0.69μ ($\Delta = -0.02$), with a rate of -0.003μ per 1,000 landings. This final period is characterised by the ongoing inability to perform rubber removal, resulting in continued friction decline to the lowest average recorded in the study.

4.8.2. Key Finding: Accelerating Degradation Rate

The degradation rate data reveal a critical pattern. Comparing the degradation rates across the study period for periods without rubber removal:

Table 4-8 Accelerating Degradation Rate

Period	Degradation Rate (μ /1,000 RWY Y landings)	Phase
Mar–Aug 2023	-0.0060	Healthy
Aug–Sep 2023	0.0000	Healthy
Jan–Jun 2024	-0.0139	Accelerating
Jun 2024–Mar 2025	-0.0010	Floor effect
Apr–Oct 2025	-0.0037	Structural
Oct 2025–Jan 2026	-0.0028	Structural

The most striking observation is the more-than-doubling of the degradation rate from -0.006μ in the early healthy phase to -0.014μ per 1,000 landings in the accelerating phase (January–June 2024). This acceleration cannot be attributed solely to the higher traffic volume during this period; the normalised rate (per 1,000 landings) explicitly controls for traffic intensity. Instead, the accelerated rate indicates that the pavement's intrinsic resistance to friction degradation had diminished.

The apparently lower rates in the later periods (2025–2026) should be interpreted cautiously. The Post-Event 3 rate of -0.004μ per 1,000 landings (April–October 2025) is lower in absolute terms than the Post-Event 2 rate, but this reflects a floor

effect: the pavement began the period at a much lower friction level (0.76μ vs. 0.89μ), meaning there was simply less friction "budget" available for degradation before a floor is reached. The absolute friction level at the end of Post-Event 3 (0.71μ) is lower than that at the end of Post-Event 2 (0.72μ), confirming the continued downward trajectory.

The critical observation across events is that the **peak recovery** after rubber removal declined from 0.89μ (Event 2) to 0.76μ (Event 3)—a 15% reduction in achievable friction—indicating that the pavement itself was progressively losing its capacity to provide adequate friction even when clean. This declining ceiling, rather than the inter-test degradation rate, is the more reliable indicator of the pavement's deteriorating condition.

2.9. Rubber Removal Effectiveness Analysis

Three rubber removal events were confirmed during the study period, and a fourth was prevented by pavement deterioration. The comparative analysis of these events reveals a clear pattern of diminishing returns that constitutes one of the study's principal findings.

Table 4-9 Rubber Removal Events — Comparative Analysis

Parameter	Event 1	Event 2	Event 3	Event 4 (Prevented)
Approximate timing	Feb–Mar 2023	Sep 2023–Jan 2024	Mar–Apr 2025	Not performed
Pre-removal avg μ	0.82	0.79	0.70	$0.71 \rightarrow 0.69$
Post-removal avg μ	0.85	0.89	0.76	—
Recovery ($\Delta\mu$)	+0.03	+0.10	+0.06	—
Post-removal min μ	0.46	0.60	0.53	—

Post-removal vs DOL	+0.03 above	+0.07 above	−0.06 below	—
Days between tests	24	129	48	—
Pavement phase	Phase 1: Healthy	Phase 1: Healthy	Phase 3: Structural	Phase 3: Critical

Source: the study airport friction test reports, Reports 1–12 (withheld for confidentiality).

Figure 4.2 (chart_02_rubber_removal_recovery.png) illustrates the recovery achieved by each event, and Figure 5.2 (chart_10_diminishing_returns.png) plots the declining trend in post-removal friction levels over time.

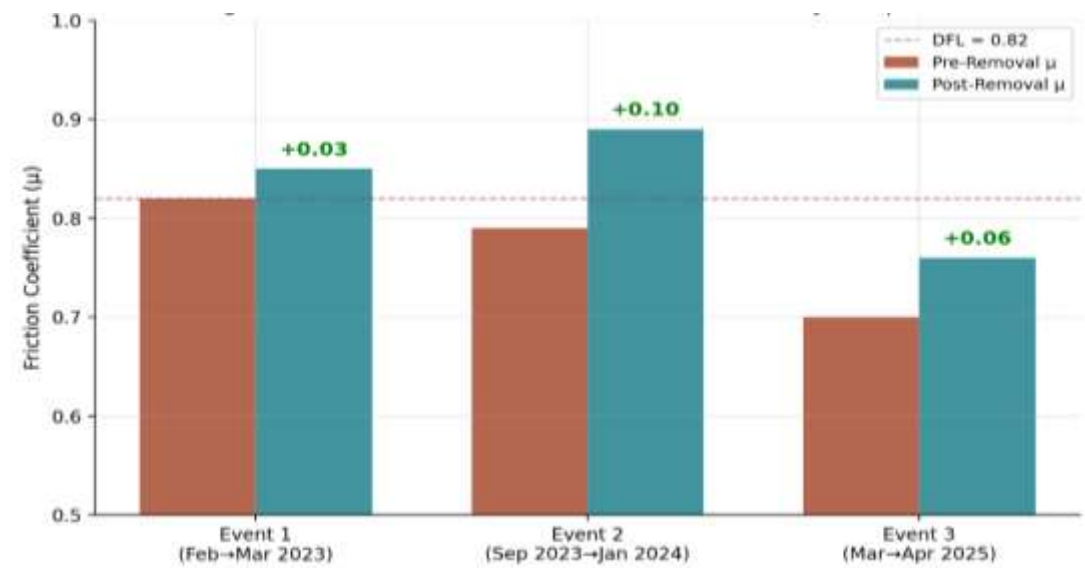


Figure 4-9 Rubber Removal Effectiveness – Recovery Comparison

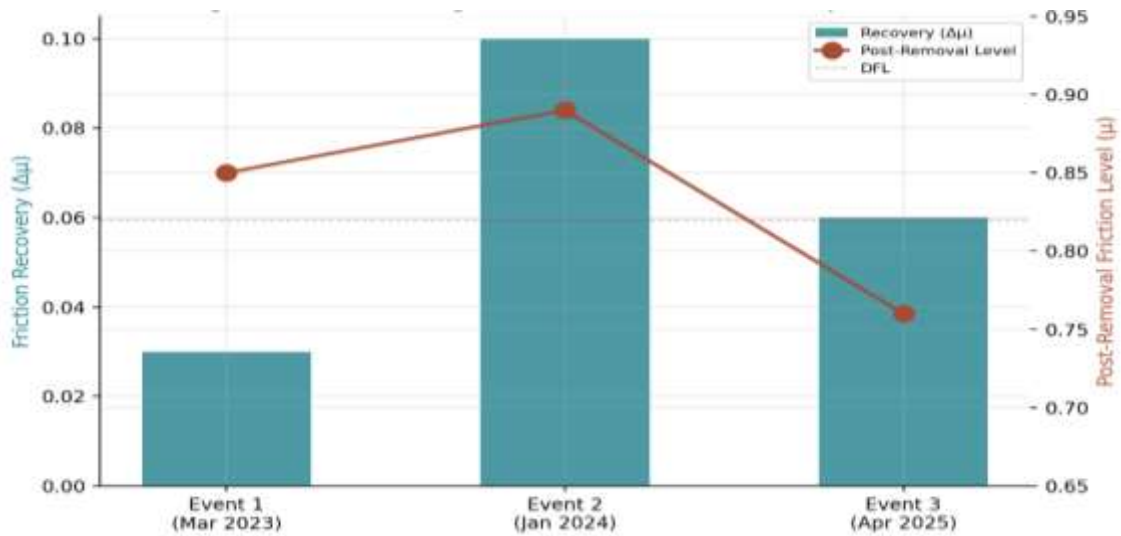


Figure 4-10 Event 1: February–March 2023

The first rubber removal event raised friction from 0.82μ to 0.85μ —a modest recovery of $+0.03\mu$. The small magnitude of recovery reflects the fact that the pavement was already in relatively good condition; the pre-removal friction of 0.82μ was at the DOL, indicating that rubber contamination was light and the pavement surface retained its intrinsic friction capacity. The post-removal result of 0.85μ confirmed that the pavement could exceed the DOL when clean, establishing a healthy baseline.

2.9.1. Event 2: September 2023–January 2024

The second rubber removal event produced the largest recovery in the dataset: friction rose from 0.79μ to 0.89μ ($\Delta = +0.10$), the highest friction value recorded in the entire study. The substantial recovery reflects effective rubber removal from a pavement surface that was still in good structural condition. Critically, the post-removal minimum friction of 0.60μ —exactly at the MPL—indicates that even at its cleanest, some runway zones were already approaching the maintenance planning threshold, an early warning sign of surface degradation in localised areas.

2.9.2. Event 3: March–April 2025

The third rubber removal event marked a qualitative shift. Despite the clear need for intervention (pre-removal average of 0.70μ , minimum of 0.28μ), the recovery achieved was only $+0.06\mu$, raising friction to 0.76μ . This post-removal level is **0.06μ below the DOL** and **0.13μ below the post-Event 2 level**. The rubber removal was

effective in removing contamination—as evidenced by the improvement in minimum friction from 0.28μ to 0.53μ —but the underlying pavement surface could no longer achieve friction levels comparable to those attained in earlier cycles.

This result confirms the **diminishing returns** hypothesis articulated in the literature review. Each rubber removal cycle, while restoring friction in the short term, imposes incremental damage on the pavement surface through binder stripping, aggregate dislodgement, and microcracking. Over successive cycles, this cumulative damage reduces the pavement's intrinsic friction capacity, meaning that each subsequent removal starts from a lower friction ceiling. The trajectory of post-removal friction peaks—0.85, 0.89, 0.76—indicates this declining ceiling when the anomalously high Event 2 result (which may reflect particularly effective removal or favourable testing conditions) is contextualised against the broader trend.

2.9.3. Event 4: Prevented

The most striking finding regarding rubber removal effectiveness is the **fourth event that could not occur**. By October 2025, friction had declined to 0.71μ , and by January 2026, to 0.69μ —with localised minimum values of 0.33μ and 0.27μ respectively. Under normal operating procedures, these values would have triggered immediate rubber removal. However, airport operations staff determined that the asphalt pavement had deteriorated to the point where the application of high-pressure water—the necessary rubber removal technique—would cause further structural damage to the pavement surface.

This prevented event represents the culmination of the diminishing returns trajectory. The pavement had crossed a critical threshold beyond which rubber removal was no longer technically feasible without incurring unacceptable additional damage. The runway had, in effect, lost access to its primary friction maintenance tool, leaving friction to decline under continued traffic loading with no available remediation short of pavement rehabilitation.

2.10. Pavement Deterioration and Compounding Degradation

The preceding analyses converge on what constitutes the **core empirical contribution** of this thesis: the identification and documentation of a compounding degradation cycle in which pavement deterioration, rubber accumulation, and

maintenance limitations interact to produce an accelerating, self-reinforcing decline in friction performance.

2.10.1. The Compounding Cycle

The compounding degradation cycle operates as follows:

1. **Rubber accumulates** on the runway surface from normal landing operations, degrading friction proportionally to cumulative traffic loading.
2. **Rubber removal is performed** to restore friction, but the high-pressure water process **damages the pavement surface** incrementally—stripping binder, dislodging aggregate, and initiating microcracks.
3. Over successive cycles, the cumulative pavement damage **reduces the pavement's intrinsic friction capacity**, meaning that each rubber removal achieves progressively less friction recovery.
4. The compromised pavement surface **accumulates rubber more rapidly** because its reduced macrotexture provides smoother surfaces for rubber adhesion, shortening the interval to the next maintenance trigger.
5. More frequent rubber removal **further accelerates pavement damage**, compounding the degradation.
6. Eventually, the pavement deteriorates to the point where rubber removal **cannot be performed at all** without risking further structural damage, eliminating the maintenance option entirely.
7. Without rubber removal, friction **declines uncontrollably** under continued traffic, approaching and potentially breaching the Minimum Friction Level.

This cycle is illustrated schematically in Figure 4.11 (chart_08_lifecycle.png).

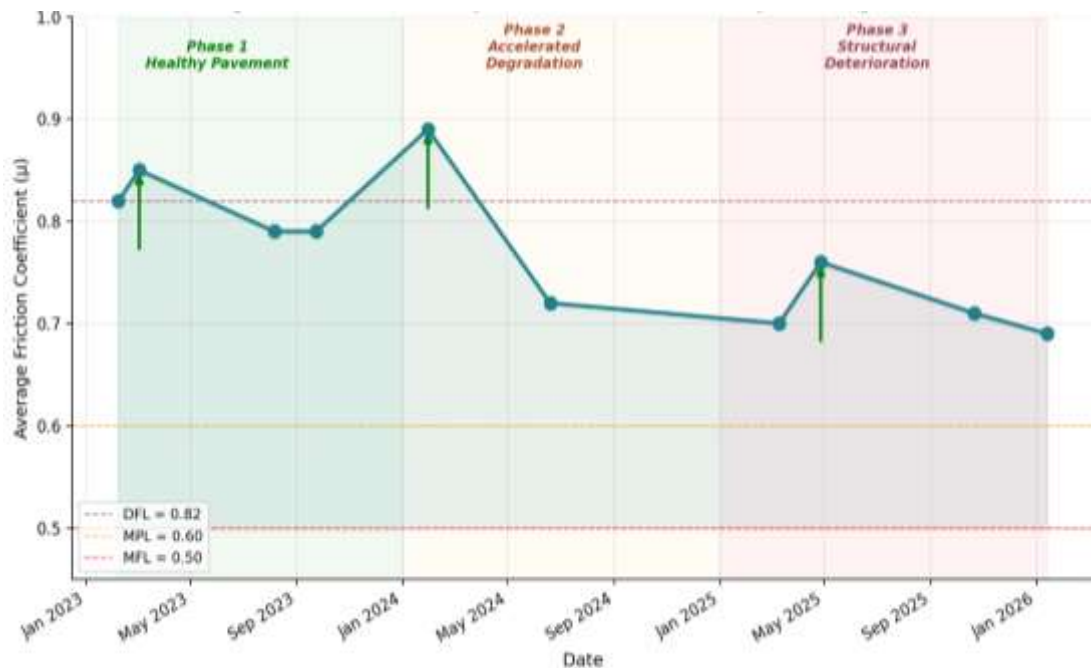


Figure 4-11 Pavement Lifecycle – Three Phases of Runway X/Y Degradation

2.10.2. Evidence from the Three Phases

The data from Runway X/Y at the study airport provide concrete evidence for each stage of this cycle:

Phase 1 — Healthy Pavement (2023): The pavement was in good condition. Rubber removal was effective, restoring friction to 0.85–0.89μ (at or above the DOL). The degradation rate was moderate at -0.006μ per 1,000 landings. The system was in equilibrium: rubber accumulated, was removed, and friction was restored to near-design levels.

Phase 2 — Accelerating Degradation (2024): The pavement began to show signs of cumulative wear. The degradation rate more than doubled to -0.014μ per 1,000 landings following the January 2024 rubber removal. Friction dropped from 0.89μ to 0.72μ in just five months—the steepest decline in the dataset. The pavement was losing its ability to resist friction degradation at the same rate as previously. The equilibrium of Phase 1 was breaking down.

Phase 3 — Structural Degradation (2025–2026): The pavement's condition had deteriorated to a critical state. Rubber removal in March–April 2025 achieved only

partial recovery (to 0.76 μ , well below the DOL of 0.82 μ). Subsequent decline brought friction to 0.71 μ by October 2025, at which point rubber removal was no longer feasible due to asphalt deterioration. By January 2026, friction had fallen to 0.69 μ overall, with minimum values of 0.27 μ —a level at which localised zones of the runway present a severe safety risk under wet conditions.

2.10.3. Critical Safety Implications

The January 2026 friction survey (Test 10) reveals the following condition:

- **Overall average:** 0.69 μ — above the MPL (0.60) but 0.13 μ below the DOL (0.82)
- **Minimum recorded value:** 0.27 μ — 46% below the MFL (0.50) and 67% below the DOL (0.82)
- **Percentage of readings below MFL:** approximately 1.27% (as indicated by the ICE artefact)
- **No rubber removal possible:** Pavement condition prevents conventional maintenance
- **No improvement since October 2025:** Friction declined further from 0.71 μ to 0.69 μ

The aggregate average of 0.69 μ , while above the MPL, masks severe localised deficiencies. The minimum friction of 0.27 μ , located in the RWY Y touchdown zone at the 6-metre lateral offset, represents a condition where aircraft braking effectiveness on a wet surface would be reduced to approximately one-third of the design level. This condition exists in precisely the zone where friction is most critical—the touchdown area where aircraft first contact the runway surface and require maximum braking performance.

2.10.4. Theoretical Significance

The compounding degradation cycle documented in this study has not been previously described in the runway friction literature with empirical longitudinal evidence. While the individual mechanisms are well-established—rubber accumulation degrades friction (ICAO, 2015), rubber removal damages pavement

(Wambold et al., 1995), and pavement deterioration reduces achievable friction (Shahin, 2005)—the **interaction** among these mechanisms to produce a self-reinforcing cycle that ultimately eliminates the maintenance option has not been empirically demonstrated in a real-world operational setting with longitudinal data spanning the full cycle from healthy pavement through maintenance infeasibility.

This finding has profound implications for runway friction management strategy. It demonstrates that the conventional reactive approach—waiting for friction to decline, then performing rubber removal—is not merely suboptimal but is inherently self-defeating in the long run. Each reactive removal cycle contributes to the cumulative pavement damage that will eventually make removal impossible. A proactive strategy that minimises the number and aggressiveness of removal cycles while maintaining adequate friction—through earlier, lighter interventions informed by traffic-based prediction—could significantly extend the pavement's functional life and delay or prevent the onset of the compounding degradation cycle.

2.11. Summary of Analytical Findings

The analysis presented in this chapter yields seven principal findings:

Finding 1: Declining Longitudinal Trend. Overall average friction on Runway X/Y declined from 0.82μ (February 2023) to 0.69μ (January 2026) over the three-year study period, representing a 16% reduction. The trend is not linear but exhibits three distinct phases—healthy, accelerating, and structural—reflecting the progressive deterioration of both surface contamination conditions and pavement structural integrity.

Finding 2: Spatial Concentration of Contamination. Rubber contamination is concentrated along the main landing gear tracks, with the 6-metre lateral offset consistently recording the lowest friction values (mean 0.73μ) compared to the 3-metre offset (0.77μ) and the 9-metre offset (0.83μ). This spatial pattern is consistent across all 10 test dates and both runway directions, confirming that the primary contamination band is centred approximately 5–7 metres from the runway centreline.

Finding 3: Directional Traffic Asymmetry. RWY Y receives approximately 65% of all landing traffic (average 1,806 landings/month) and shows consistently lower friction than RWY X across all lateral offsets, with seasonal peaks during the Hajj period (June–July) when RWY Y share exceeds 75%.

Finding 4: Accelerating Degradation Rates. The friction degradation rate per 1,000 RWY Y landings more than doubled from -0.006μ in the healthy phase (2023) to -0.014μ in the accelerating phase (2024), indicating progressive loss of the pavement's intrinsic resistance to friction degradation under traffic loading.

Finding 5: Diminishing Rubber Removal Returns. Post-removal friction levels declined progressively across the three confirmed events: 0.85μ (Event 1), 0.89μ (Event 2), and 0.76μ (Event 3). The third event failed to restore friction to the DOL, and the fourth event could not be performed at all due to pavement deterioration.

Finding 6: ICAO Frequency Non-Compliance. The actual rubber removal frequency at the study airport (approximately annually) falls significantly short of ICAO recommendations (semi-annually based on landings; every four months based on mass). This gap contributes to heavier rubber accumulation and the need for more aggressive removal when maintenance is eventually performed.

Finding 7: Compounding Degradation Cycle. The study documents a self-reinforcing degradation cycle in which pavement deterioration → inability to remove rubber → continued friction decline → approaching safety-critical levels. This cycle represents the most significant finding of the study and provides empirical evidence for a mechanism that, while theoretically anticipated, has not been previously documented with longitudinal operational data. The January 2026 minimum friction of 0.27μ —46% below the MFL, in a condition where no maintenance can be performed—represents the direct consequence of this compounding cycle.

Together, these seven findings paint a comprehensive picture of a runway pavement system progressing through a lifecycle of degradation. The early phases are characterised by manageable friction decline responsive to conventional maintenance. The intermediate phase sees accelerating degradation and diminishing maintenance effectiveness. The terminal phase features the loss of maintenance capability and uncontrollable friction decline toward safety-critical thresholds. The identification of this lifecycle trajectory—and the compounding mechanisms that drive it—constitutes the primary empirical contribution of this thesis.

These findings form the empirical foundation for the discussion of their implications (Chapter 5) and the development of the integrated decision-support framework (Chapter 6) presented in the subsequent chapters.

Chapter 5 DISCUSSION

3.1.Introduction

The preceding chapter presented a detailed, multi-source analysis of friction performance, air traffic loading, rubber removal outcomes, and pavement condition at a major Saudi international airport (hereinafter referred to as "the study airport"). This chapter interprets those findings within the broader context of runway friction science, pavement engineering theory, and aerodrome operational management, and synthesises them into answers for each research question.

Four overarching themes structure the discussion. First, the relationship between cumulative traffic and friction degradation is examined, with the study airport data benchmarked against international literature. Second, a three-phase pavement lifecycle model—healthy, accelerated degradation, and structural deterioration—is articulated as an original contribution that explains the non-linear trajectory observed at the study airport. Third, the diminishing returns of successive rubber removal events are analysed through the lens of pavement material science and compared with earlier empirical findings. Fourth, the operational, regulatory, and safety implications of these findings are explored, including the fundamental trade-off between short-term friction restoration and long-term pavement integrity, the aggregate-versus-local friction reporting paradox, the case for predictive rather than reactive maintenance, and the compliance gap between ICAO/GACA guidance and actual practice at the study airport. Together, these themes provide the interpretive foundation for the decision-support framework presented in Chapter 6 and the conclusions and recommendations articulated in Chapter 7.

3.2. Traffic–Friction Relationship: Evidence and Implications

3.2.1. Cumulative Traffic as the Primary Driver of Friction Decline

The study airport dataset provides compelling, quantitative evidence that cumulative landing traffic is the primary determinant of friction degradation on Runway X/Y. Over the three-year study period (February 2023 to January 2026), the overall runway average friction coefficient declined from 0.82μ to 0.69μ —a 16% reduction—as the runway accumulated an estimated 76,000 total landings on RWY Y alone. The correlation between traffic load and friction loss is visible in two complementary

forms: (a) the directional asymmetry between the two runway ends, and (b) the inter-test degradation rates normalised to landing counts.

RWY Y receives approximately 65% of all landings (~1,806 landings per month on average), while RWY X handles approximately 34% (~957 landings per month). Consistent with this loading differential, the RWY Y direction exhibits systematically lower friction across all ten tests. In the most recent survey (January 2026), the RWY Y 6-metre offset average was 0.61μ with a minimum of 0.27μ , compared with the RWY X 6-metre offset at 0.66μ with a minimum of 0.33μ . The RWY Y touchdown zone therefore experiences friction levels roughly 8–10% lower than the RWY X touchdown zone at any given point in time. This directional asymmetry is exactly what a traffic-driven degradation model would predict: more landings deposit more rubber, filling the pavement macrotexture more quickly and reducing the drainage channels that sustain wet-friction capacity.

This finding is consistent with the models proposed by De Luca et al. (2016), who correlated GripTester friction readings with cumulative aircraft operations at an Italian aerodrome and established that friction decay follows a broadly logarithmic relationship with traffic volume. Similarly, Gopal and Timm (2019) demonstrated that rubber deposition depth in the touchdown zone correlates with both the number and weight of landing operations. The study airport data extend these findings into the specific context of a high-traffic Saudi aerodrome operating under extreme climatic conditions, confirming the generalisability of the traffic–friction relationship.

3.2.2. Quantified Degradation Rates and Their Acceleration

The degradation rate analysis presented in Chapter 4 reveals that friction loss per unit of traffic is not constant—it accelerates over the runway's operational life. In the earliest non-removal period for which complete data are available (March to August 2023), friction declined at a rate of -0.006μ per 1,000 RWY Y landings. By the January–June 2024 period, the degradation rate had more than doubled to -0.014μ per 1,000 RWY Y landings—representing a 133% increase in the vulnerability of the pavement surface to traffic-induced friction loss.

The period from April 2025 to October 2025 recorded a degradation rate of -0.0037μ per 1,000 landings, and the October 2025 to January 2026 period showed -0.0028μ per 1,000 landings. While these later rates are lower in absolute terms than the peak of

-0.014μ , they must be interpreted in context. By this stage, friction had already declined to $0.71\text{--}0.69\mu$. At lower friction levels, the relationship between rubber deposition and measured friction may become sub-linear: the pavement texture is already substantially filled, and additional rubber produces diminishing incremental friction reduction. The deceleration of the degradation rate at low friction does not indicate pavement recovery; rather, it reflects a floor effect approaching the asymptotic minimum friction that the rubber-contaminated surface can sustain.

3.2.3. Seasonal Traffic Surges and the Hajj/Umrah Effect

the study airport's traffic profile is dominated by the Islamic pilgrimage calendar. During June–July (Hajj season), RWY Y landings peak at 2,200–2,527 per month—roughly 40% above the annual average. The Umrah high season (October–March) also generates sustained elevated traffic. These seasonal surges concentrate rubber deposition into compressed time windows.

The most dramatic friction decline in the dataset occurred in the January–June 2024 interval: a -0.17μ drop over approximately 12,197 RWY Y landings. This period encompassed the Hajj build-up, with RWY Y receiving 2,039–2,280 landings per month in March–July 2024. The combination of elevated traffic volume, high ambient temperatures (which soften tyre rubber and promote greater deposition per landing), and a relatively fresh post-removal surface (following the January 2024 rubber removal) created conditions for exceptionally rapid friction loss.

This finding has direct planning implications. Rubber removal scheduled in the weeks before the Hajj surge would start the high-traffic season with maximum friction headroom, whereas removal scheduled after the surge addresses the accumulated contamination reactively—after the safety-critical peak demand period has already been navigated with diminished friction margins.

3.2.4. The Role of Aircraft Mix

Although the available traffic data are disaggregated only by landing direction and not by aircraft type, inference about the fleet mix is possible from the airport's operational profile. the study airport serves primarily narrow-body aircraft (Airbus A320 family, Boeing 737 family) on domestic and regional routes, supplemented by wide-body aircraft (Airbus A330, Boeing 777, Boeing 787) on international Hajj and Umrah charter operations. The mass-based analysis in the dataset estimates RWY Y annual

mass at approximately 2.9 billion kilograms, placing the runway in the 2,405M–3,969M kg bracket under ICAO weight-based classification. This mass figure, when compared with the landing count, implies a mean aircraft mass of approximately 134,000 kg per landing—consistent with a fleet mix weighted toward medium narrow-body and heavy wide-body aircraft.

Wide-body aircraft impose greater tyre loads per wheel, higher touchdown speeds, and larger contact patch areas, all of which contribute to heavier rubber deposition per event (Yager, 2013). Their disproportionate contribution to total rubber mass means that the Hajj/Umrah charter operations—which bring a higher proportion of wide-body movements—accelerate friction degradation beyond what the simple landing count would predict. This observation reinforces the recommendation, developed in the framework chapter, for a weighted landing metric that accounts for aircraft category when estimating cumulative rubber load.

3.2.5. Comparison with International Literature

The traffic–friction relationship documented at the study airport merits comparison with findings from other aerodromes to assess its consistency and identify context-specific variations.

De Luca et al. (2016) measured friction decay at an Italian airport using a GripTester and found that friction declined approximately logarithmically with cumulative traffic operations, with the steepest decline occurring in the first 5,000–10,000 operations after rubber removal. The study airport data are broadly consistent with this pattern: the steepest per-unit-traffic decline occurred in the Phase 2 period (January–June 2024), when a freshly cleaned surface was subjected to over 12,000 RWY Y landings in rapid succession. The -0.014μ per 1,000 landings rate at the study airport is at the upper end of the range reported in the Italian study, likely reflecting the combined effect of higher traffic density and the extreme thermal environment at the study airport.

Baimukhametov and White (2026) analysed friction lifecycle dynamics at four Australian airports and found that friction reduction rates were highest in touchdown zones—consistent with the study airport observation—and that these rates gradually decreased as friction declined. Their study also observed that regular rubber removal "significantly restores friction, sometimes exceeding post-construction levels." This

observation aligns with the study airport Event 2 result (post-removal $\mu = 0.89$, exceeding the DOL of 0.82) but diverges from the Event 3 result (post-removal $\mu = 0.76$, well below DOL), suggesting that the Australian runways in their study had not yet entered the Phase 2–3 transition that characterises the study airport pavement.

Biancardo et al. (2020) developed a broad-based decision-making procedure for runway friction decay analysis that incorporated traffic data and aircraft performance characteristics into predictive models. Their calibrated models demonstrated that friction degradation could be predicted with reasonable accuracy using traffic variables alone—a finding that supports the traffic monitoring layer of the framework proposed in Chapter 6. However, their framework did not incorporate a pavement condition gating criterion, which the study airport data demonstrate is essential for avoiding the Phase 3 failure scenario.

Nazarie and Musc (2026) conducted field measurements of friction reduction generated by rubber deposits, correlating friction coefficient measurements with visual assessments of rubber contamination severity. Their findings confirmed that rubber deposits fill both macrotexture and microtexture, affecting aircraft braking characteristics—consistent with the mechanism underlying the friction decline observed at the study airport. Their emphasis on the touchdown zone as the primary area of concern further validates the zone-specific analysis approach adopted in this study.

The convergence of findings across these diverse aerodrome contexts—Italian, Australian, and Saudi—strengthens the conclusion that the traffic–friction relationship is a fundamental, universal phenomenon that applies across pavement types, climates, and traffic profiles. The specific coefficients (degradation rate per 1,000 landings) vary with local conditions, but the direction, shape, and qualitative characteristics of the relationship are consistent. This universality supports the transferability of the decision-support framework's structure, while its calibration mechanism accommodates the local variation in coefficients.

5.3. The Pavement Lifecycle Model

5.3.1. A Three-Phase Model

The study airport data reveal a coherent, three-phase lifecycle for the asphalt pavement surface of Runway X/Y as it relates to friction capacity and maintainability. This lifecycle model constitutes a key contribution of the present study. While the general principle of pavement degradation is well established in the highway engineering literature (Shahin, 2005; de Solminihaç et al., 2018), its specific manifestation in the context of runway friction management—where both traffic-induced rubber contamination and maintenance-induced surface damage interact—has not previously been documented in the Saudi aerodrome context.

Phase 1: Healthy Pavement (2023). During this phase, the pavement surface retains its designed macrotexture and microtexture. Aggregate particles are angular and firmly bonded by the asphalt binder. Rubber accumulates in the surface voids but can be removed effectively, restoring friction to near the Design Friction Level ($DOL = 0.82\mu$). The evidence for this phase at the study airport includes: (a) the January 2024 post-removal friction of 0.89μ —the highest value recorded in the entire dataset, exceeding the DOL by 0.07μ ; (b) the early degradation rate of -0.006μ per 1,000 landings, indicating that the pavement surface resists traffic-induced friction loss effectively; and (c) the stability of friction between August and September 2023 ($0.79\mu \rightarrow 0.79\mu$ over 2,828 RWY Y landings), suggesting that at moderate contamination levels, the pavement's intrinsic texture maintains functional friction even without rubber removal. During Phase 1, reactive maintenance—testing and removing rubber at scheduled intervals—is reasonably effective because the pavement responds well to treatment and the friction recovery is substantial.

Phase 2: Accelerated Degradation (2024). In this transitional phase, the cumulative effects of traffic loading and prior rubber removal operations begin to compromise the pavement surface. The degradation rate more than doubles, from -0.006μ to -0.014μ per 1,000 landings. The accelerated degradation is attributable to two converging mechanisms. First, repeated rubber removal has progressively stripped binder material and eroded aggregate surfaces, reducing the intrinsic texture of the pavement. The first rubber removal in early 2023 would have been the most benign in terms of surface damage; the second removal (late 2023/early 2024) would have imposed

additional damage on an already slightly degraded surface. Second, the increasing traffic volume in 2024 (which saw several months exceeding 3,000 total landings) means that rubber accumulates faster, necessitating either more frequent removal or acceptance of longer periods at lower friction levels.

The hallmark of Phase 2 is the dramatic friction decline following the January 2024 rubber removal: from the peak of 0.89μ down to 0.72μ over just five months and 12,197 RWY Y landings. This -0.17μ decline is the steepest absolute drop in the dataset and represents a deterioration rate more than 130% higher than the Phase 1 baseline. During Phase 2, the reactive maintenance model begins to fail: the interval between need-for-removal and the next scheduled test may not be short enough to detect the rapid approach toward the Maintenance Planning Level ($MPL = 0.60\mu$), and the rubber removal, when performed, restores friction to progressively lower levels.

Phase 3: Structural Deterioration and Maintenance Incapacity (2025–2026).

Phase 3 represents the most critical and novel finding of this study. By early 2025, the cumulative impact of traffic loading, rubber accumulation, and successive rubber removal operations had degraded the asphalt pavement to the point where the fourth rubber removal operation could not be performed. According to the operational records, the pavement had deteriorated so severely that applying the high-pressure water blasting necessary for rubber removal would further damage the surface—potentially causing delamination, aggregate loss, or cracking that would be more dangerous than the rubber contamination itself.

This finding introduces the concept of a compounding degradation cycle unique to Phase 3:

1. Pavement surface deteriorates from cumulative traffic and maintenance
2. Deteriorated pavement cannot sustain rubber removal without further damage
3. Rubber cannot be removed, so it continues to accumulate
4. Accumulated rubber further reduces friction
5. Friction declines toward and below safety thresholds
6. Without rubber removal capability, friction will not recover absent resurfacing

The evidence for Phase 3 at the study airport is stark. After the April 2025 rubber removal (Event 3), friction was restored to only 0.76μ —well below the 0.85μ and 0.89μ achieved in Events 1 and 2, respectively. By October 2025, friction had declined to 0.71μ , and despite the operational need for rubber removal, it was not performed due to pavement condition concerns. By January 2026, friction reached 0.69μ (with localised minima of 0.27μ), and the runway continued to operate without rubber removal. The pavement had, in effect, reached the end of its friction-functional life: it could neither provide adequate intrinsic friction nor accept the maintenance intervention designed to restore friction.

5.3.2. Comparison with Literature

The three-phase model is conceptually consistent with, but extends, the general pavement deterioration models described by Shahin (2005) and de Solminihac et al. (2018), which characterise pavement degradation as an initially slow, then accelerating, then rapid-decline process. However, those models address structural pavement distress (cracking, rutting, roughness) rather than friction-specific degradation. The study airport model adds a friction-specific dimension that integrates rubber contamination dynamics with surface texture deterioration and maintenance-induced damage—a combination not previously articulated in the literature.

The model also extends the findings of Baimukhametov and White (2026), who documented friction lifecycle dynamics at four Australian airports. Their study observed that friction reduction rates are highest in touchdown zones and that degradation rates gradually decrease as friction declines—consistent with the deceleration of degradation observed in the study airport's Phase 3. However, Baimukhametov and White reported that rubber removal "significantly restores friction, sometimes exceeding post-construction levels," a finding that applies primarily to pavements still in Phase 1 or early Phase 2 of the lifecycle model proposed here. The study airport data demonstrate that this restoration capacity is not permanent—it diminishes with each successive cycle and ultimately disappears in Phase 3.

5.3.3. Implications for Pavement Management

The lifecycle model has profound implications for pavement management planning. Current practice at the study airport—and at many aerodromes globally—treats rubber

removal as an indefinitely repeatable maintenance intervention. The Phase 3 finding challenges this assumption. Airport operators must recognise that:

- Each rubber removal event has a cumulative, irreversible cost to pavement surface integrity.
- The pavement surface has a finite capacity to sustain rubber removal cycles.
- Predictive modelling of pavement condition is as important as predictive modelling of friction decline.
- Resurfacing or rehabilitation must be scheduled proactively, before the pavement enters Phase 3, because once Phase 3 is reached, the compounding cycle eliminates the operator's primary friction management tool.

5.3.4. Identifying the Phase Transitions: Practical Indicators

A critical practical question arising from the lifecycle model is: how can an aerodrome operator identify which phase their pavement is in, given that the transition boundaries are not sharp but gradual? The study airport data suggest several observable indicators for each transition:

Indicators of Phase 1 → Phase 2 transition:

- Post-removal friction begins to decline from historical maximum (at the study airport, the post-removal friction after Event 2 was 0.89μ ; had Event 3 achieved only $0.82\text{--}0.85\mu$, this would have signalled the transition)
- Degradation rate per 1,000 landings increases by more than 50% relative to the Phase 1 baseline
- Time between rubber removal events shortens, even at constant traffic levels
- Visual inspection reveals early signs of binder stripping or aggregate exposure in the touchdown zones
-

Indicators of Phase 2 → Phase 3 transition:

- Post-removal friction falls below the DOL (0.82μ), indicating that even clean pavement can no longer achieve design-level friction

- Degradation rate decelerates despite continued traffic loading (the "floor effect" discussed in Section 5.2.2)—not because the pavement is improving but because friction is approaching an asymptotic minimum
- Visual inspection reveals moderate-to-severe surface distress: ravelling, crack networks, loose aggregate, binder bleeding
- Maintenance staff report difficulty in achieving clean rubber removal—residual staining persists despite standard treatment
- Pavement engineers assess that standard rubber removal pressures (>20,000 psi) risk causing additional surface damage

At the study airport, the Phase 2 → Phase 3 transition occurred between approximately mid-2024 and early 2025, as evidenced by the Event 3 post-removal friction (0.76μ , well below DOL) and the subsequent operational determination that the fourth rubber removal could not be performed. The framework proposed in Chapter 6 formalises these indicators into a structured scoring system that enables operators to identify their pavement's lifecycle phase and adjust maintenance strategies accordingly.

5.3.5. Comparison with Highway Pavement Lifecycle Models

The three-phase model proposed here bears structural similarity to the well-established pavement deterioration models used in highway engineering. Shahin's (2005) Pavement Condition Index (PCI) lifecycle model describes an initial slow-deterioration phase, followed by an inflection point beyond which deterioration accelerates rapidly—the "critical PCI" zone. De Solminihac et al. (2018) formalised this into a lifecycle cost framework that identifies the optimal intervention timing as the point just before the acceleration phase begins.

The runway friction lifecycle model extends these concepts in two important ways. First, it introduces the friction-specific dimension: in addition to structural distress (cracking, rutting), the model tracks the pavement's capacity to provide surface friction as mediated by both inherent texture and rubber contamination. Second, it incorporates the maintenance-induced damage mechanism: each rubber removal cycle degrades the surface incrementally, creating a feedback loop between maintenance activity and pavement deterioration that is absent from the highway models (where maintenance generally restores rather than degrades condition).

This feedback loop makes the runway friction lifecycle inherently more dynamic than the highway pavement lifecycle. In highway engineering, timely maintenance extends pavement life; in runway friction engineering, the same maintenance activity (rubber removal) simultaneously restores friction and shortens the pavement's friction-functional life. This paradox is unique to the runway friction domain and represents a novel contribution to the pavement management literature.

5.4. Diminishing Returns of Rubber Removal

5.4.1. Quantified Recovery Decline

The three confirmed rubber removal events at the study airport demonstrate a clear pattern of diminishing friction recovery:

Table 5-1 Quantified Recovery Decline

Event	Date	Pre-Removal μ	Post-Removal μ	Recovery ($\Delta\mu$)	Post-Removal vs. DOL
1	Feb–Mar 2023	0.82	0.85	+0.03	+0.03 above DOL
2	Sep 2023–Jan 2024	0.79	0.89	+0.10	+0.07 above DOL
3	Mar–Apr 2025	0.70	0.76	+0.06	–0.06 below DOL
4 (prevented)	—	0.71→0.69	Not performed	—	—

Event 1's modest recovery (+0.03 μ) reflects the relatively low rubber accumulation at the time; the pavement was near DOL even before removal, so the incremental gain was small. Event 2 produced the largest recovery (+0.10 μ) and the highest post-removal friction (0.89 μ) in the dataset, indicating that the pavement was still in Phase 1 and fully capable of responding to maintenance. Event 3, however, is the critical transition. Despite a lower starting point (0.70 μ , implying greater rubber accumulation and thus greater potential for recovery), Event 3 restored friction to only 0.76 μ —0.13 μ below the Event 2 post-removal level. The pavement's maximum

achievable friction had declined by 14.6% between Event 2 and Event 3, even though the pavement was nominally cleaned of rubber in both cases.

This decline in maximum achievable friction—the friction level obtained immediately after thorough rubber removal—is the clearest evidence of irreversible pavement surface degradation caused by the cumulative effects of traffic, environmental aging, and the rubber removal process itself.

5.4.2. The Mechanism of Surface Degradation

The diminishing returns phenomenon is attributable to the mechanical interaction between the high-pressure water (or other removal agent) and the pavement surface. High-pressure water blasting, the predominant rubber removal technique employed at the study airport, operates at pressures of 10,000–40,000 psi. At these pressures, the water jet is not selective—it removes rubber deposits but also strips asphalt binder from the aggregate interface, dislodges fine aggregate particles, and erodes the microtexture of exposed aggregate surfaces (Patterson, 2017; Pullen et al., 2014).

After a single removal cycle on a new pavement, the damage is imperceptible. After multiple cycles, however, the cumulative effects become measurable:

- **Binder stripping:** progressive loss of the bituminous mastic that binds aggregate particles reduces the cohesion of the surface matrix. Aggregate particles become loosely held and susceptible to dislodgement under traffic loading.
- **Macrotexture reduction:** fine aggregate and binder material flushed from the inter-aggregate voids during removal reduces the depth of the drainage channels essential for wet-friction performance.
- **Microtexture polishing:** each removal cycle slightly abrades the exposed aggregate surfaces, smoothing the micro-asperities that provide the tyre–pavement contact friction at low speeds.
- **Surface oxidation:** the removal of binder exposes fresh asphalt to UV radiation and thermal cycling, accelerating oxidative aging of the surface layer in a major international airport in Saudi Arabia's extreme climate—with summer temperatures routinely exceeding 40°C—this oxidative process is particularly aggressive (Al-Sahli & Al-Kahtani, 2018).

These processes are individually minor per cycle but compound multiplicatively over the pavement's maintenance history. The result is a progressive decline in the friction ceiling—the maximum friction the pavement can provide when clean of rubber. When this ceiling drops below the DOL (as occurred at the study airport between Events 2 and 3), the pavement can no longer be maintained at its design friction level through rubber removal alone, regardless of how thorough the removal is.

5.4.3. The Paradox of Preventive Maintenance

The diminishing returns finding creates what may be termed the "rubber removal paradox": the very intervention designed to restore safety (rubber removal) progressively destroys the surface's capacity to provide safety (intrinsic friction). This paradox is not unique to the study airport—it is inherent in any high-pressure removal technique applied repeatedly to an asphalt surface. However, it is exacerbated by:

- **High traffic volumes** that necessitate more frequent removal
- **Extreme heat** that accelerates post-removal oxidative aging
- **Under-frequency removal** (i.e., removal performed less often than ICAO recommends), which allows heavier rubber accumulation that requires more aggressive treatment to remove

The resolution of the paradox lies in optimisation: selecting removal parameters (pressure, nozzle type, number of passes) that minimise pavement damage while achieving adequate rubber removal, scheduling removal more frequently (so less aggressive treatment suffices), and planning resurfacing before the pavement enters Phase 3. This optimisation logic is incorporated into the decision-support framework presented in Chapter 6.

5.4.4. Comparison with Published Findings

The diminishing returns observed at the study airport are consistent with the findings reported in the limited literature on long-term rubber removal effects. Horne and Griswold (1975) documented friction changes due to high-pressure water-jet cleaning at multiple U.S. airports and observed that post-cleaning friction levels were sensitive to the number of prior cleaning cycles and the aggressiveness of the treatment parameters. Although their study did not extend to the point of maintenance

incapacity observed at the study airport, the declining trend in post-cleaning recovery was evident.

Pullen et al. (2014) conducted field evaluations of ultra-high-pressure water systems for runway rubber removal and noted that surface damage indicators (aggregate polishing, binder loss) increased with repeated application, particularly at higher pressures. Their findings directly support the mechanism described in Section 5.4.2 and the pressure-dependent technique selection incorporated into the framework in Chapter 6.

Kim et al. (2016) investigated the development of a "rubber removal primer"—a chemical pre-treatment designed to reduce the water pressure and mechanical force required for rubber removal, thereby minimising pavement damage. Their work acknowledges the fundamental problem addressed by this study: that conventional high-pressure removal imposes unacceptable cumulative damage on asphalt surfaces. The primer approach represents one potential mitigation strategy that could extend the pavement's friction-functional life by reducing per-cycle damage.

Patterson (2017), in the ACRP Synthesis 83 report on runway rubber removal methods and environmental impacts, comprehensively reviewed the state of practice and identified pavement surface damage as a significant concern across all removal techniques, though the severity varies by method. Chemical removal was associated with less surface damage than ultra-high-pressure water blasting but raised environmental and regulatory compliance issues. Shot blasting achieved thorough rubber removal but imposed the greatest surface texture modification. These trade-offs further motivate the multi-criteria technique selection logic incorporated into the proposed framework.

5.4.5. Implications for Maintenance Strategy

The diminishing returns finding has several direct implications for maintenance strategies:

1. **Track post-removal friction as a pavement health metric.** The post-removal friction level is a more sensitive indicator of pavement condition than visual inspection alone, because it captures the cumulative effect of micro-scale damage that is not visible to the naked eye.

2. **Establish a minimum acceptable post-removal friction threshold.** If post-removal friction cannot be restored above the MPL (0.60μ), rubber removal has effectively reached end-of-life utility and pavement rehabilitation should be initiated.
3. **Optimise removal parameters to minimise damage.** Using the minimum effective water pressure and fewest passes necessary to restore friction above the MPL—rather than pursuing maximum rubber removal—extends the pavement's friction-functional life.
4. **Invest in pavement-friendly removal technologies.** Research into lower-damage alternatives—chemical removal, low-pressure water with surfactants, cryogenic removal—could extend the number of removal cycles a pavement can sustain before entering Phase 3.
5. **Plan resurfacing proactively.** When post-removal recovery trends indicate the approach of Phase 3, resurfacing should be planned and budgeted before maintenance capability is lost, avoiding the operational crisis that occurs when neither rubber removal nor adequate friction is achievable.

5.5. The Safety–Pavement Trade-Off

5.5.1. The Fundamental Dilemma

Every rubber removal decision involves a trade-off that is rarely acknowledged explicitly: removing rubber now improves short-term friction but imposes long-term damage to the surface that will degrade future friction capacity. The decision-maker is, in effect, borrowing from the pavement's future friction potential to restore present-day safety.

During Phase 1, this trade-off is heavily weighted toward removal: the pavement is robust, the damage per removal cycle is negligible, and the friction recovery is substantial. The benefit-to-cost ratio of rubber removal is very high.

During Phase 2, the trade-off becomes more balanced. Each removal cycle achieves less recovery and imposes proportionally greater damage on an increasingly vulnerable surface. The benefit-to-cost ratio declines. At this stage, the decision-maker faces a genuine optimisation problem: should rubber removal be performed at higher frequency with lighter parameters (preserving pavement integrity but accepting

residual rubber) or at lower frequency with more aggressive parameters (removing more rubber but accelerating surface degradation)?

During Phase 3, the trade-off reverses. Rubber removal would inflict more damage (from the mechanical stress on a deteriorated surface) than benefit (from the modest friction recovery achievable). At the study airport, this reversal manifested as the operational decision to not perform the fourth rubber removal, despite friction at 0.71μ and declining. The pavement engineering assessment determined that the risk of structural surface failure from high-pressure water blasting exceeded the benefit of the friction restoration that could be achieved.

5.5.2. Data-Driven Evidence from the study airport

The study airport data provide quantitative evidence for the progression of this trade-off. In Event 2 (January 2024), rubber removal produced a net friction gain of $+0.10\mu$ —representing approximately 12% improvement in friction. In Event 3 (April 2025), the net gain was $+0.06\mu$ —approximately 8.6% improvement, but from a lower baseline. Furthermore, the post-Event 3 level of 0.76μ was 0.13μ below the post-Event 2 level of 0.89μ , meaning that the pavement had permanently lost 0.13μ of friction capacity between the two removals—a loss of 14.6% of the DOL. The pavement's friction "bank account" was being drawn down faster than the maintenance process could replenish it.

If we project this trajectory, the next rubber removal (had it been feasible) would likely have achieved a post-removal friction of approximately $0.70\text{--}0.74\mu$ —barely above the pre-removal level of earlier tests. The pavement would then be operating in a regime where rubber removal produces marginal or negligible friction improvement while continuing to damage the surface. This the threshold at which rubber removal ceases to be a viable maintenance strategy and rehabilitation (resurfacing or reconstruction) becomes the only effective intervention.

5.5.3. Implications for Decision-Making

The safety–pavement trade-off requires a decision framework that evaluates not just current friction versus thresholds but also the trajectory of post-removal recovery over time. A runway where post-removal friction has declined by more than 10% from the historical maximum should be flagged for pavement condition assessment. A runway

where post-removal friction cannot reach the MPL should be scheduled for rehabilitation, as rubber removal has become ineffective.

The proposed framework in Chapter 6 formalises this logic by tracking post-removal recovery as a key pavement health indicator and establishing quantitative thresholds for escalating from rubber removal to resurfacing recommendations.

5.5.4. The Optimal Intervention Point

The safety–pavement trade-off analysis suggests the existence of an optimal intervention point—a friction level and pavement condition combination at which rubber removal delivers the maximum net benefit (friction recovery minus pavement damage cost). While precise identification of this optimum requires lifecycle cost modelling beyond the scope of this study, the study airport data provide qualitative guidance:

The optimal intervention point lies in the upper portion of the Phase 2 zone, where:

- Friction has declined to approximately 0.72–0.75 μ (moderately contaminated, requiring only moderate-pressure treatment)
- Pavement condition is still at Level 3 or above (surface can tolerate standard removal parameters)
- Cumulative traffic since last removal is approximately 10,000–12,000 RWY Y landings (consistent with semi-annual removal at average traffic)
- Post-removal recovery is expected to return friction to at least 0.80 μ (near DOL)

Intervening earlier than this point (friction still above 0.75 μ , light contamination) incurs unnecessary cost and pavement damage for marginal friction benefit.

Intervening later (friction below 0.70 μ , heavy contamination) requires more aggressive treatment, causes disproportionate pavement damage, and yields diminishing friction recovery.

The proposed framework's predictive capability enables the operator to schedule maintenance at this optimal point by forecasting when friction will reach the target range, rather than discovering the deterioration after it has progressed past the optimum. This timing optimisation is one of the framework's most significant practical benefits.

5.5.5. Implications for Resurfacing Planning

The safety–pavement trade-off analysis also informs resurfacing planning. The lifecycle model indicates that the transition from Phase 2 to Phase 3 occurs when post-removal friction can no longer reach the DOL—the pavement has lost enough intrinsic friction capacity that even a perfectly clean surface cannot provide design-level performance. At the study airport, this transition occurred between January 2024 (post-removal $\mu = 0.89$, above DOL) and April 2025 (post-removal $\mu = 0.76$, below DOL).

This transition should trigger the initiation of resurfacing planning—not immediate resurfacing (which requires substantial lead time for engineering design, contractor procurement, and budgeting), but the formal commencement of the planning and approval process. At the study airport's observed transition rate, the lead time from Phase 2 onset to Phase 3 (maintenance incapacity) was approximately 12–18 months. If resurfacing planning requires 18–24 months from initiation to execution, then planning should ideally commence at the Phase 1 → Phase 2 transition, when the first signs of declining post-removal recovery appear.

The framework supports this by maintaining a long-term view of pavement health through the post-removal recovery tracking mechanism, alerting operators when the recovery trend indicates the approach of Phase 2 and projecting the likely timeline to Phase 3 based on current degradation trajectories.

5.6. The Aggregate versus Local Friction Problem

5.6.1. The Masking Effect of Average Reporting

The January 2026 friction data illustrate a dangerous deficiency in single-number friction reporting. The overall runway average of 0.69μ exceeds the MPL of 0.60μ and might, at first glance, suggest satisfactory friction performance. However, this aggregate figure conceals severe localised deficiencies. The minimum friction reading of 0.27μ —recorded at the 6-metre offset in the RWY Y direction—is 46% below the MFL of 0.50μ and represents a segment where aircraft braking effectiveness on a wet surface would be reduced to approximately one-third of the design level.

The spatial analysis reveals the extent of the problem. In the RWY Y touchdown zone (approximately 400–600 metres from the threshold), friction at the 6-metre offset

drops to 0.27–0.42 μ across multiple consecutive 50-metre segments. The RWY X touchdown zone shows a similar pattern, with 6-metre offset values of 0.33–0.49 μ over a 500-metre span. These sub-MFL zones extend over a combined runway length of approximately 1,000 metres at the most contaminated lateral position—nearly one-quarter of the total runway length.

5.6.2. Implications for Safety Assessment

The aggregate-versus-local paradox has significant implications for safety assessment methodology. If aerodrome operators report only portion averages (the A/B/C segments), the critical touchdown zone deficiencies may be diluted by higher values in adjacent sections, producing a portion average that appears acceptable when in fact some segments within the portion are critically deficient.

This finding supports the ICAO recommendation to evaluate friction using the minimum 100-metre rolling average within each portion, not the portion average. However, even this approach may be insufficient if the 100-metre window does not capture the full spatial extent of the critical zone. The analysis at the study airport demonstrates that the most severe contamination occurs in a relatively narrow band (approximately 300–600 metres from each landing threshold), and this band may span the boundary between two portions, potentially splitting the contaminated zone across two separate evaluations.

The proposed decision-support framework addresses this limitation through zone-based analysis—evaluating friction by geographic functional zone (touchdown zone, mid-section, recovery zone) rather than by arbitrary portion divisions.

5.6.3. The 6-Metre Offset Anomaly: Linking Friction to Fleet Geometry

A particularly instructive finding from the spatial analysis is that the 6-metre offset from the runway centreline consistently records the lowest friction, rather than the 3-metre offset that one might naively expect to be closest to the heaviest rubber deposits. This observation is directly attributable to the geometry of the predominant aircraft types operating at the study airport.

For narrow-body aircraft—the Airbus A320 family and Boeing 737 series, which constitute the majority of operations—the main landing gear track width places the outboard tyres approximately 4–7 metres from the runway centreline. The 6-metre CFME test line therefore passes through the precise lateral zone of maximum rubber

deposition. The 3-metre line, by contrast, falls between the left and right main gear tracks (for aircraft tracking close to the centreline), in a relative "valley" of lower rubber accumulation. The 9-metre line falls outside the primary gear track zone entirely, explaining its consistently higher friction values.

This finding has two important implications. First, it confirms that friction testing at multiple lateral offsets is essential for capturing the true severity of rubber contamination. A single centreline test (as was historically common practice at some aerodromes) would underestimate the contamination severity by missing the peak-deposition zone. Second, it provides precise guidance for targeted rubber removal: the 4–8 metre band from the centreline on each side represents the primary treatment zone, where the most intensive rubber removal effort should be concentrated. Treating the full 60-metre runway width uniformly would waste resources on the lightly contaminated outer zones while potentially providing insufficient treatment to the critical inner zones.

For airports with a high proportion of wide-body aircraft, the peak rubber deposition band would be wider (approximately 5–10 metres from the centreline), reflecting the greater main gear track width of Boeing 777, Airbus A330, and similar types. During Hajj charter operations at the study airport, the temporary increase in wide-body movements would shift the rubber deposition pattern, potentially extending the contaminated band toward the 9-metre offset. The framework's seasonal pattern recognition component is designed to detect such shifts and adjust maintenance targeting accordingly.

5.6.4. Recommendations for Reporting Methodology

The aggregate-versus-local friction paradox observed at the study airport supports the following recommendations for friction reporting methodology:

1. **Report zone-specific minimum values.** In addition to the overall runway average and portion averages, the friction report should explicitly identify the minimum 100-metre rolling average within each touchdown zone and each lateral offset. The most critical value—the lowest minimum across all zones and offsets—should be prominently highlighted as the safety-determining metric.

2. **Include spatial context in NOTAMs.** When below-MFL conditions are identified, the NOTAM should specify the affected zone (e.g., "RWY Y touchdown zone, 400–600m from threshold, 6m offset") rather than merely stating "runway may be slippery when wet." This spatial specificity enables pilots to adjust their approach planning (e.g., aiming for a later touchdown point beyond the contaminated zone, if operationally feasible).
3. **Develop colour-coded friction maps.** Graphical representation of friction data as a colour-coded map of the runway surface—with green, yellow, and red zones corresponding to above-MPL, between-MPL-and-MFL, and below-MFL areas—provides an intuitive visualisation for non-specialist decision-makers and can be included in safety briefings and operational communications.
4. **Standardise multi-offset testing.** While ICAO recommends testing at the point of maximum rubber deposition, not all aerodromes conduct tests at multiple offsets. The study airport analysis demonstrates the significant information loss when only a single offset is tested—the 8–12% difference between the 6-metre and 9-metre offsets represents the difference between satisfactory and critically deficient friction in the same runway section.

5.7.Reactive versus Predictive Maintenance

5.7.1. Limitations of the Reactive Approach—Evidence from the study airport

The current maintenance practice at the study airport follows the reactive paradigm: friction tests are conducted at intervals; when results indicate deterioration, rubber removal is scheduled; the operation takes 7–10 days; and a confirmation test verifies the outcome. This approach has two fundamental weaknesses exposed by the data.

First, the interval between tests may be too long to detect rapidly deteriorating conditions. The steepest degradation period in the dataset (January–June 2024, -0.17μ over five months) would have breached the MPL approximately 3–4 months after the post-removal test—well before the next scheduled assessment. During this interval, the runway operated with declining and potentially sub-MPL friction in the most contaminated zones, without triggering a maintenance response.

Second, once a below-threshold condition is detected, the logistics of rubber removal introduce additional delay. Equipment mobilisation, chemical procurement, and runway closure scheduling can add 2–4 weeks between detection and the start of treatment, followed by 7–10 days for the operation itself. Total elapsed time from detection to restoration can thus be 3–6 weeks—during which the runway continues to operate with inadequate friction.

5.7.2. The Predictive Alternative

A predictive maintenance system would operate fundamentally differently. Using the degradation rates established through historical data—for example, the -0.014μ per 1,000 RWY Y landings observed during Phase 2—the system would project forward from the most recent friction measurement to estimate when friction will reach the MPL and MFL. Taking the January 2024 post-removal value of 0.89μ as an example:

- At -0.014μ per 1,000 landings and $\sim 1,806$ RWY Y landings per month:
- Monthly degradation = $-0.014 \times 1.806 = -0.025\mu$ per month
- Time to reach MPL (0.60μ) from 0.89μ : $(0.89 - 0.60) / 0.025 = 11.6$ months
- Time to reach MFL (0.50μ) from 0.89μ : $(0.89 - 0.50) / 0.025 = 15.6$ months

This projection would have enabled the operator to schedule rubber removal at approximately month 10—well before the MPL was breached—and to plan the closure window during a relatively lower-traffic period. The maintenance would be performed when contamination is moderate (requiring less aggressive treatment) rather than heavy (requiring maximum pressure and passes), thereby reducing pavement damage per cycle.

The predictive approach also accommodates seasonal variation. If the system detects that the upcoming months include Hajj season, it can adjust the degradation rate upward (reflecting the traffic surge) and advance the projected maintenance date accordingly. Pre-Hajj rubber removal becomes a planned, optimised intervention rather than an emergency response to post-Hajj friction crisis.

5.7.3. Cost Implications

The cost differential between reactive and predictive maintenance is substantial, though precise quantification requires data not available in this study. However, qualitative analysis indicates several cost drivers:

- **Emergency mobilisation premium:** unplanned rubber removal requires expedited equipment scheduling and potentially overtime labour.
- **Operational disruption costs:** unplanned runway closures during high-traffic periods generate cascading airline delays.
- **Pavement damage costs:** aggressive treatment of heavy contamination causes greater surface degradation than moderate treatment of lighter contamination.
- **Reduced pavement life:** each aggressive removal cycle shortens the time to resurfacing, bringing forward a capital expenditure of tens of millions of SAR.

The rubber removal cost at the study airport is approximately 7 million SAR per event. If predictive maintenance could reduce the number of removal events by even one per pavement lifecycle—by enabling lighter, more frequent interventions that achieve the same cumulative effect with less surface damage—the savings in deferred resurfacing alone would likely exceed the investment in the predictive system.

5.7.4. Illustrative Predictive Scenario from the study airport Data

To demonstrate the practical value of the predictive approach, consider how the framework would have operated if deployed at the study airport from January 2024 onward, using the Event 2 post-removal data (0.89μ) as the starting point.

Month 0 (January 2024): Post-removal friction = 0.89μ . Cumulative traffic counter reset to zero. Degradation rate initialised from Phase 1 data at -0.006μ per 1,000 landings. Projected MPL breach: $\sim 48,300$ RWY Y landings, or approximately 26.7 months at average traffic.

Month 3 (April 2024): Cumulative RWY Y landings $\approx 5,929$ (January–March 2024 actual data). If an interim friction test was conducted at this point and showed, say, 0.80μ , the system would recalculate the degradation rate: $(0.89 - 0.80) / 5.929 = -0.015\mu$ per 1,000 landings. This significantly higher than the Phase 1 baseline, triggering an immediate alert. New MPL projection: $(0.80 - 0.60) / 0.015 \times 1,000 = \sim 13,333$ additional landings, or approximately 7.4 months. The system would flag: "MPL breach projected in early November 2024. Recommend scheduling rubber removal for September–October 2024."

Month 5 (June 2024): The actual June 2024 test showed 0.72μ after approximately 12,197 cumulative landings. Under the predictive system, this test would have already

been triggered by the enhanced monitoring alert at Month 3. The system would now update: degradation rate confirmed at approximately -0.014μ per 1,000 landings (Phase 2). MPL projected to be reached in approximately 4,300 additional landings, or 2.4 months. MFL projected at approximately 11,400 additional landings, or 6.3 months. The system would recommend: "Immediate rubber removal required. Schedule closure for late July or early August, before Hajj season traffic begins."

In actuality, rubber removal was not performed until March 2025—approximately 15 months after Event 2, by which time friction had reached 0.70μ with minima of 0.28μ . The predictive system would have intervened approximately 9 months earlier, when contamination was lighter and the pavement was less degraded—enabling a less aggressive treatment that would have caused less surface damage and achieved better friction recovery.

This illustrative scenario demonstrates that the data required for predictive maintenance already exist within the study airport operational data streams. The gap is not in data availability but in the analytical framework that connects the data to decision-making.

5.7.5. Limitations of the Predictive Approach

While the predictive approach offers significant advantages, several limitations must be acknowledged:

1. **Model uncertainty in early deployment.** With limited historical data, the degradation rate estimates carry wide confidence intervals. The first two to three cycles of framework operation may produce imprecise projections, requiring calibration through actual test-versus-predicted comparisons.
2. **Non-linear degradation.** The assumption of approximately linear degradation within each phase is a simplification. Actual degradation may follow more complex trajectories influenced by environmental factors (rainfall events, temperature extremes, UV exposure) that are not captured by traffic data alone.
3. **Data quality dependence.** The framework's predictions are only as reliable as the input data. Inconsistencies in CFME testing procedures, tyre type changes (as occurred at the study airport in 2023), or gaps in traffic records introduce noise that can degrade prediction accuracy.

4. **Organisational adoption barriers.** The transition from reactive to predictive maintenance requires cultural change, resource investment, and sustained institutional commitment. The framework may face resistance from personnel accustomed to the simplicity of threshold-based decision-making.

These limitations are manageable through the feedback and calibration mechanism (Component 5 of the framework), which systematically improves model accuracy with each successive data cycle. The framework is designed to operate initially with high uncertainty and progressively narrow its prediction confidence as data accumulate.

5.8. Operational Constraints in the Saudi Context

5.8.1. Runway Closure Requirements

Rubber removal at the study airport requires closure of Runway X/Y for 7–10 days. During closure, all operations divert to the secondary runway (A/B), which at 3,050 metres $\times$ 45 metres is significantly shorter and narrower than the main runway (4,335 m $\times$ 60 m). This diversion may impose weight restrictions on certain wide-body aircraft types, potentially requiring fuel stops, payload reductions, or route cancellations—all carrying commercial and operational costs.

The closure requirement creates a strong institutional bias toward deferring rubber removal. Operations managers face immediate, tangible costs (runway closure, airline disruption) if maintenance is performed, versus diffuse, probabilistic risks (friction-related incident) if it is deferred. This asymmetry in the perceived cost–benefit equation leads to systematic under-maintenance—a phenomenon clearly visible in the study airport data, where the actual rubber removal frequency (approximately annual) falls well short of the ICAO-recommended frequency (semi-annual).

5.8.2. Hajj and Umrah Scheduling Pressures

The pilgrimage seasons impose absolute operational constraints. During peak Hajj (approximately June–July) and high Umrah periods (October–March), the study airport handles dramatically elevated traffic, and runway availability is paramount. Rubber removal during these periods would be operationally catastrophic—yet these are precisely the periods when friction degrades most rapidly due to the traffic surge.

This temporal mismatch creates a structural vulnerability: the periods of greatest maintenance need coincide with the periods of greatest maintenance infeasibility. The predictive approach resolves this by scheduling rubber removal in the windows immediately preceding the traffic surge—typically May for pre-Hajj and September for pre-Umrah high season—ensuring maximum friction headroom when it is most needed.

5.8.3. The Delayed Maintenance Spiral

When rubber removal is deferred beyond the optimal timing, a self-reinforcing spiral develops:

1. Friction falls below MPL, requiring more aggressive removal when eventually performed
2. More aggressive removal causes greater pavement damage
3. Greater pavement damage accelerates future friction degradation
4. Faster degradation necessitates even more frequent maintenance
5. The operational pressure to defer maintenance intensifies as the costs of closure increase

This spiral is visible in the study airport data. The extended interval between rubber removal Events 2 (January 2024) and 3 (April 2025)—approximately 15 months, well beyond the ICAO-recommended 6-month interval—allowed friction to deteriorate to 0.70μ with minima of 0.28μ . The subsequent removal restored friction to only 0.76μ , and by October 2025, the pavement had deteriorated to the point where the next removal could not be performed at all. The deferred maintenance spiral had reached its terminal stage.

5.8.4. Cost Considerations

The financial dimension of the maintenance dilemma at the study airport warrants explicit discussion. Rubber removal at the study airport costs approximately 7 million SAR per event—a figure that encompasses equipment mobilisation, consumables (water, chemicals), contractor fees, and the direct costs of runway closure management. This cost, while substantial, is a fraction of the cost of the runway resurfacing that becomes necessary when the pavement reaches Phase 3 and rubber removal is no longer viable.

A full resurfacing of the asphalt sections of Runway X/Y (approximately 3,835 metres after excluding the concrete threshold areas, at 60 metres width) would involve removal of the existing surface course, re-application of a new surface course, curing, marking, and recommissioning. Based on industry estimates for comparable projects in the Gulf region, such a resurfacing would cost in the range of 40–80 million SAR, depending on the scope of underlying structural repairs required.

The economic logic is therefore clear: each rubber removal event that costs 7 million SAR but extends the pavement's friction-functional life by 6–12 months is a cost-effective investment, provided it does not accelerate the approach to Phase 3.

However, a rubber removal event that costs 7 million SAR and causes sufficient pavement damage to bring the resurfacing date forward by 6–12 months is a net economic loss—the operator would have been better served by accepting the lower friction (with operational mitigations) and investing the 7 million SAR toward the resurfacing budget.

This cost trade-off analysis reinforces the need for the pavement condition gating criterion in the proposed framework: rubber removal should only be performed when the expected friction recovery benefit exceeds the expected pavement damage cost, assessed in terms of its impact on the remaining friction-functional life.

5.8.5. Institutional and Contractual Constraints

At the study airport, runway maintenance is managed within the concession agreement between the airport operating company and the General Authority of Civil Aviation (GACA). The concession structure creates specific institutional dynamics:

- **Performance requirements:** the concession may specify minimum friction standards that the operator must maintain, creating a regulatory obligation to perform rubber removal even when the operator's engineering assessment suggests the pavement cannot sustain it.
- **Budget cycle misalignment:** rubber removal costs must be budgeted within annual operating expenditure cycles, while resurfacing is a capital expenditure item that may require separate approval processes, potentially spanning multiple fiscal years.
- **Contractor availability:** rubber removal at the study airport requires specialised contractors with ultra-high-pressure water blasting equipment.

These contractors serve multiple airports in the region, and scheduling conflicts during peak seasons (when multiple airports need rubber removal simultaneously before their respective peak traffic periods) can introduce delays.

These institutional constraints are not unique to the study airport—they are common across the global airport industry, particularly at airports operated under concession or public-private partnership models. The framework addresses these constraints by providing advance scheduling capability (60+ days before maintenance is needed), enabling the operator to secure contractor availability, budget allocation, and regulatory approval in advance of the maintenance window.

5.9. ICAO/GACA Compliance Gap

5.9.1. Frequency Analysis

Based on the traffic data, RWY Y averages approximately 1,806 landings per month, placing it in the ICAO bracket of 930–2,700 monthly landings. This bracket specifies:

- **Friction survey frequency:** every 3 months
- **Rubber removal frequency:** every 6 months (semi-annual)

The mass-based analysis paints an even more demanding picture. RWY Y's annual mass throughput of approximately 2.9 billion kilograms places it in the 2,405M–3,969M kg bracket, which specifies rubber removal every 4 months.

Actual rubber removal frequency at the study airport has been approximately annual—roughly double the landing-based interval and triple the weight-based interval. Over the three-year study period, only three rubber removal events were completed, compared with the six that would have been required under the landing-based ICAO recommendation or nine under the weight-based recommendation.

5.9.2. Consequences of the Compliance Gap

The compliance gap directly contributed to the observed outcomes. Less frequent removal meant heavier rubber accumulation between events, which in turn required more aggressive treatment to remove—accelerating pavement degradation. Had

rubber removal been performed at the semi-annual frequency recommended by ICAO, each removal event would have addressed lighter contamination, allowed the use of lower water pressures and fewer passes, and restored friction more completely with less pavement damage. The pavement might not have reached Phase 3 within the study period.

5.9.3. Regulatory Implications

The findings suggest that the current ICAO frequency recommendations, while appropriate as minimum standards, may need to be supplemented with traffic-adjusted, condition-based scheduling that accounts for:

- Seasonal traffic surges that compress rubber accumulation into shorter periods
- Pavement age and condition, which affect the surface's vulnerability to maintenance damage
- Post-removal recovery trends, which indicate declining pavement health
- Weight-based loading, which more accurately reflects rubber deposition than landing counts alone

The decision-support framework in Chapter 6 operationalises these adjustments within a unified monitoring and decision system that complements the existing ICAO/GACA regulatory structure.

Chapter 6 DECISION-SUPPORT FRAMEWORK

6.1. Framework Overview

The analysis and discussion presented in Chapters 4 and 5 have established that runway friction management at the study airport is governed by the interaction of multiple, dynamic factors: traffic loading, rubber accumulation, friction degradation, pavement surface condition, rubber removal effectiveness, and operational constraints. Current practice addresses these factors in isolation—friction is measured and compared to thresholds, rubber removal is scheduled reactively, and pavement condition is assessed separately. The result, as demonstrated by the data, is sub-optimal maintenance timing, accelerated pavement degradation, and a compounding cycle that ultimately eliminated the operator's primary maintenance tool.

This chapter presents an integrated decision-support framework designed to address these deficiencies by unifying the relevant data streams into a single, coherent analytical process. The framework comprises five interconnected components that operate in a continuous monitoring-analysis-decision-action-feedback cycle:

1. **Traffic Monitoring Layer** — tracks cumulative landing operations and forecasts rubber accumulation
2. **Friction Trend Analysis Layer** — monitors friction trajectories and projects threshold breaches
3. **Pavement Condition Assessment** — evaluates the surface's capacity to sustain maintenance
4. **Maintenance Decision Logic** — determines optimal action, timing, and technique
5. **Feedback and Calibration** — updates models with new data after each cycle

The framework is illustrated conceptually in the flowchart referenced as Figure 6.1 (chart_12_framework_flowchart.png). It is designed for implementation at operational aerodromes with existing friction testing programmes and can be deployed initially using spreadsheet-based tools, progressing to dedicated software as the value is demonstrated.

Figure 6.1: Decision-Support Framework Flowchart

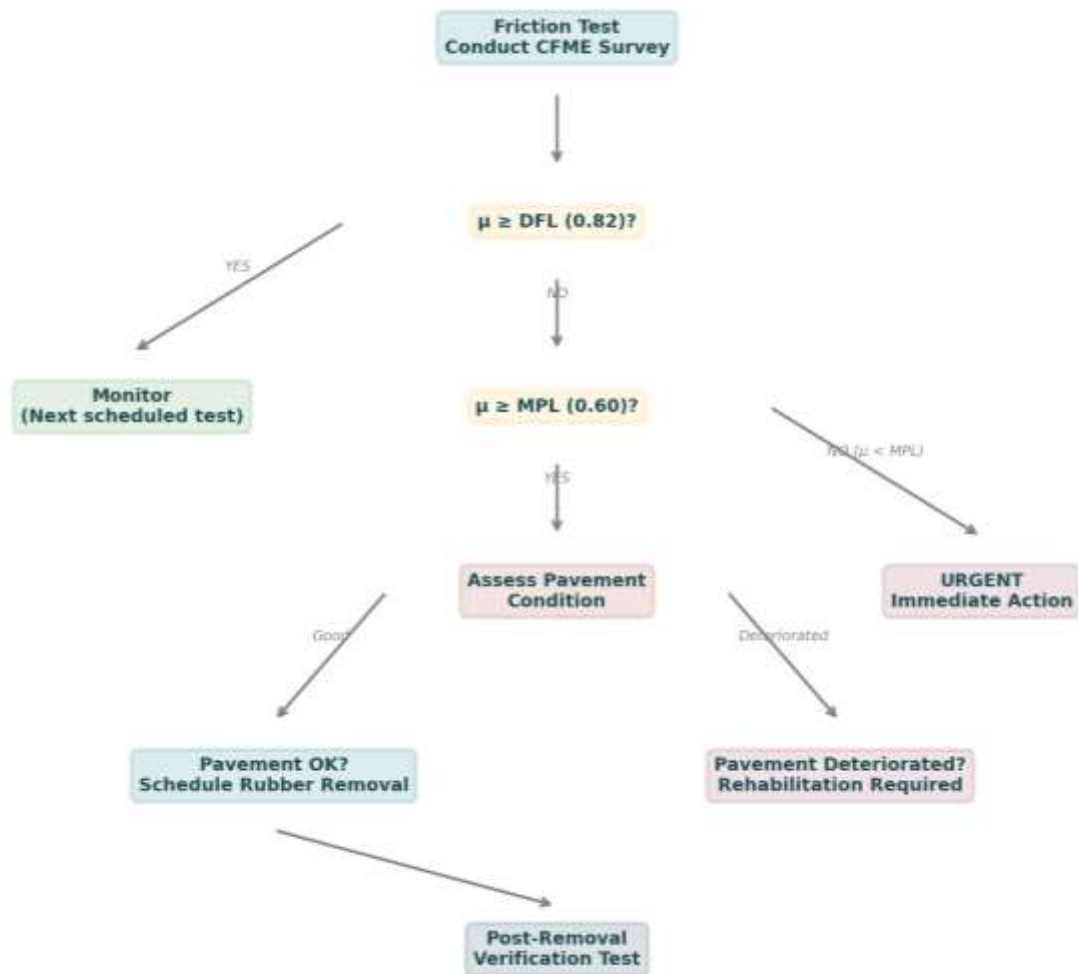


Figure 6-1 Framework Flowchart

6.1.1. Design Principles

The framework is built on five design principles derived from the study airport case study findings:

Principle 1: Multi-source data convergence. No single data source—friction tests, traffic counts, pavement inspections, or maintenance logs—provides a complete picture of the friction management challenge. The framework requires convergence of all four data streams to produce reliable recommendations. The study airport case demonstrates the consequences of single-source decision-making: friction tests alone triggered rubber removal without consideration of pavement condition, leading to the Phase 3 failure.

Principle 2: Zone-specific analysis. Aggregate metrics mask critical localised conditions. The framework evaluates each functional zone (touchdown zone, mid-section, recovery zone) and each lateral offset (3m, 6m, 9m) independently, ensuring that the most severely affected zone drives the maintenance timeline. At the study airport, the RWY Y 6-metre offset touchdown zone was consistently the most critical location—a finding invisible in the overall runway average.

Principle 3: Trend-based rather than threshold-based decisions. A single friction value compared to a threshold provides no information about whether friction is stable, declining slowly, or declining rapidly. The same friction value of 0.65μ carries very different implications depending on whether it represents a stable condition or the midpoint of a steep decline toward the MFL. The framework analyses the rate and direction of change, not just the current level.

Principle 4: Pavement condition as a decision input. Current friction management frameworks treat the pavement as a passive surface that receives treatment. The study airport experience proves that the pavement is an active constraint: its condition determines whether treatment is viable, what parameters can be used, and what recovery can be expected. The framework elevates pavement condition from an afterthought to a primary decision input.

Principle 5: Continuous learning. The framework improves with each cycle through feedback and calibration. Initial deployments may have limited predictive accuracy, but the systematic comparison of predicted versus actual outcomes enables progressive refinement. After two to three annual cycles, the framework should achieve prediction accuracy sufficient to plan maintenance within a window of one to two weeks of the actual threshold breach date.

6.1.2. Relationship to Existing Frameworks

The proposed framework builds upon and extends several existing management systems:

- **ICAO Doc 9137 (Airport Services Manual, Part 2)** provides the foundational methodology for friction testing, threshold assessment, and maintenance triggering. The framework accepts ICAO thresholds (DOL, MPL, MFL) as given and adds predictive analytics above the ICAO minimum requirements.

- **ACRP Synthesis 83 (Patterson, 2017)** reviews rubber removal methods and their impacts. The framework incorporates Patterson's findings on technique-specific pavement damage into its technique selection logic.
- **Biancardo et al. (2020)** developed a decision-making procedure for runway friction decay analysis using machine learning. The proposed framework shares the objective of integrating traffic and friction data but adds pavement condition assessment and the lifecycle phase concept—dimensions not addressed by Biancardo et al.
- **Baimukhametov and White (2025, 2026)** reviewed runway friction regulation and analysed friction lifecycle dynamics at Australian airports. Their recommendation for updated testing intervals based on observed reduction rates is incorporated into the framework's traffic monitoring layer.

The framework's distinctive contribution is the integration of these elements—previously treated in isolation—into a unified operational workflow with the pavement viability gating criterion as its central innovation.

6.2.Component 1: Traffic Monitoring Layer

6.2.1. Cumulative Landing Counter

The traffic monitoring layer maintains a running count of landings on each runway end, disaggregated by direction. At the study airport, this means separate counters for RWY Y and RWY X landings, reset after each rubber removal event. The counter is sourced from the aerodrome's air traffic management system (ATMS) and updated daily.

The cumulative landing count serves as the primary predictor of rubber accumulation between friction test events. Based on the study airport data, the relationship between cumulative RWY Y landings and friction decline can be approximated as:

- Phase 1 pavement: $\Delta\mu \approx -0.006 \times (\text{cumulative RWY Y landings} / 1,000)$
- Phase 2 pavement: $\Delta\mu \approx -0.014 \times (\text{cumulative RWY Y landings} / 1,000)$

These coefficients are calibrated from the study airport dataset and would be re-estimated for other aerodromes during implementation.

6.2.2. Cumulative Mass Tracker

Because heavier aircraft deposit more rubber per landing, a landing count alone underestimates the rubber load from wide-body operations and overestimates it from light aircraft movements. The cumulative mass tracker addresses this by accumulating the estimated total mass of all landing aircraft since the last removal event, calculated from the aircraft type data available in the ATMS.

The study airport data show an average monthly mass throughput of approximately 2.907 billion kg on RWY Y, corresponding to an estimated mean landing mass of 134,000 kg per aircraft. During Hajj charter periods, the mean landing mass increases substantially due to the higher proportion of wide-body aircraft, providing a more sensitive indicator of rubber accumulation than landing counts alone.

6.2.3. ICAO Bracket Automatic Classification

The layer automatically classifies the runway into the appropriate ICAO monitoring bracket based on the rolling three-month average landing count and the rolling annual mass throughput. At the study airport, this would identify the runway as requiring:

- Friction survey: every 3 months (landing-based) or monthly (if peak traffic months are considered independently)
- Rubber removal: every 6 months (landing-based) or every 4 months (mass-based)

The automatic classification ensures that the monitoring frequency is adjusted dynamically as traffic patterns change, rather than relying on a fixed schedule that may become outdated as the airport grows.

6.2.4. Seasonal Pattern Recognition

The layer incorporates a seasonal decomposition algorithm that identifies recurring traffic patterns from the historical data. At the study airport, this would detect the June–July Hajj surge, the October–March Umrah elevation, and the August–September relative trough. The seasonal patterns feed into the maintenance decision logic to enable pre-positioning of rubber removal before anticipated high-traffic periods.

6.2.5. Real-Time versus Monthly Tracking Options

The traffic monitoring layer can be implemented at two levels of granularity, depending on the aerodrome's data infrastructure:

Monthly tracking (minimum requirement). Landing counts and aircraft type distribution are compiled monthly from ATMS logs. The cumulative traffic counter is updated monthly, and trend analysis performed quarterly. This approach is suitable for initial deployment and can be implemented using existing manual data compilation processes.

Real-time tracking (recommended for high-traffic airports). Landing events are captured automatically through the ATMS data feed, with each event classified by runway end, aircraft type, and estimated mass. The cumulative counter updates in real time, enabling immediate alerts when traffic-based thresholds are exceeded. This approach requires integration between the framework's data system and the ATMS, but provides significantly higher resolution for maintenance timing optimisation.

At the study airport, monthly tracking would be sufficient for initial deployment, given that the average monthly traffic (~2,800 total landings) provides adequate resolution for the degradation rate calculations. However, the transition to real-time tracking should be prioritised as the framework matures, particularly during Hajj season when weekly traffic variations can be substantial (peak weeks may see 50% higher traffic than the monthly average, concentrating rubber deposition into shorter periods).

6.3. Component 2: Friction Trend Analysis Layer

6.3.1. Degradation Rate Calculation

Following each friction test, the layer calculates the current degradation rate by comparing the new results to the previous test, expressed as:

- **μ per 1,000 RWY Y landings:** the primary traffic-normalised metric
- **μ per month:** the time-normalised metric, useful for scheduling
- **μ per 1,000 tonnes mass:** the weight-normalised metric, most accurate for mixed fleet operations

The calculation is performed separately for each functional zone:

- RWY Y touchdown zone (3m, 6m, and 9m offsets)
- Mid-section (all offsets)
- RWY X touchdown zone (3m, 6m, and 9m offsets)

Zone-specific degradation rates ensure that the most rapidly deteriorating zone drives the maintenance timeline, rather than being averaged with healthier zones.

6.3.2. Moving Average Tracking

To smooth measurement variability and identify persistent trends, the layer maintains a rolling three-test moving average of the degradation rate. This moving average provides a more stable basis for threshold projection than any single inter-test rate, which may be affected by measurement conditions, tyre type changes, or anomalous environmental factors.

6.3.3. Predictive Modelling: Threshold Projection

Using the current friction level and the degradation rate, the layer projects the estimated date when friction will reach the MPL (0.60 μ) and MFL (0.50 μ) for each zone. The projection incorporates:

- **Current friction level** (most recent test, zone-specific)
- **Degradation rate** (moving average, zone-specific)
- **Forecast traffic** (from the traffic monitoring layer, adjusted for seasonal patterns)

For example, applying the study airport Phase 2 degradation rate of -0.014μ per 1,000 landings to the January 2026 RWY Y 6-metre friction of 0.61 μ :

- Landings needed to reach MPL (0.60 μ): $(0.61 - 0.60) / 0.014 \times 1,000 = \sim 714$ landings
- At $\sim 1,806$ landings/month: approximately 12 days
- Landings needed to reach MFL (0.50 μ): $(0.61 - 0.50) / 0.014 \times 1,000 = \sim 7,857$ landings
- At $\sim 1,806$ landings/month: approximately 4.3 months

This projection would have triggered an immediate critical alert, indicating that the RWY Y touchdown zone at 6-metre offset was already at the MPL and approaching the MFL within months.

6.3.4. Anomaly Detection

The layer flags unexpected deviations from the predicted trajectory—for example, a sudden acceleration or deceleration in friction decline that cannot be explained by traffic changes. Anomalies may indicate:

- Equipment malfunction or calibration drift
- Change in tyre type (as occurred at the study airport in 2023 with the T49-to-ASTM transition)
- Unusual surface conditions (spillage, construction activity, weather effects)
- Incipient pavement failure not yet visible to inspection

Anomaly flags trigger additional investigation before the standard decision logic applies.

6.4. Component 3: Pavement Condition Assessment

6.4.1. Visual Inspection Protocol

The pavement condition component incorporates a structured visual inspection protocol conducted at defined intervals (recommended quarterly, aligned with friction testing). The protocol evaluates:

- **Surface distress:** cracking (type, severity, extent), ravelling, potholing
- **Texture condition:** visible smoothing, binder bleeding, aggregate exposure/loss
- **Drainage adequacy:** standing water patterns, macrotexture depth (measured by sand-patch or laser profiling)
- **Joint and edge condition:** for the concrete threshold sections

Each parameter is scored on a standardised scale, and the composite score represents the pavement's current surface condition.

6.4.2. Surface Condition Scoring

The surface condition score is expressed on a five-level scale:

Table 6-1 Surface Condition Scoring

Level	Condition	Description	Rubber Removal Viability
5	Excellent	New or recently resurfaced; full texture integrity	Fully viable; standard parameters
4	Good	Minor wear; texture largely intact	Viable; standard parameters
3	Fair	Moderate wear; visible texture loss in touchdown zones	Viable with reduced parameters
2	Poor	Significant texture loss; binder stripping; early ravelling	Marginally viable; minimum parameters only
1	Critical	Severe deterioration; aggregate loss; widespread ravelling	Not viable; resurfacing required

6.4.3. Gating Criterion: Pavement Viability for Rubber Removal

This the key innovation of the framework. Current friction management frameworks worldwide do not include a formal assessment of whether the pavement can sustain rubber removal before scheduling the intervention. The study airport experience demonstrates the consequences of this omission: the operator was confronted with a situation where friction was critically low but rubber removal could not be performed because the pavement could not tolerate the mechanical stress.

The framework introduces a mandatory gating criterion: before any rubber removal is scheduled, the pavement condition score must be evaluated. If the score is at Level 2 (Poor) or Level 1 (Critical), rubber removal is either restricted to minimum-impact parameters or replaced with alternative interventions (surface treatment, partial resurfacing, or full rehabilitation).

This gating criterion transforms the maintenance decision from a simple binary (remove/don't remove) to a multi-dimensional assessment that accounts for both the need for friction restoration and the pavement's capacity to accept the treatment.

6.4.4. Post-Removal Recovery Tracking

The component tracks the post-removal friction level achieved after each rubber removal event and compares it to historical values for the same runway section. A declining trend in post-removal recovery (as observed at the study airport: $0.85\mu \rightarrow 0.89\mu \rightarrow 0.76\mu$) is an early warning of cumulative pavement degradation and triggers escalation to pavement engineering assessment.

6.4.5. Integration with Friction Data: Cross-Referencing Condition and Performance

The pavement condition assessment gains particular analytical power when cross-referenced with friction trend data. Consider two scenarios:

Scenario A: Declining friction with good pavement condition. If friction is declining but pavement condition is rated Level 4–5, the decline is attributable primarily to rubber contamination. Rubber removal will be effective, and standard parameters can be applied with confidence. This scenario corresponds to Phase 1 of the lifecycle model.

Scenario B: Declining friction with deteriorating pavement condition. If friction is declining and pavement condition is rated Level 2–3, the decline reflects both rubber contamination and intrinsic pavement degradation. Rubber removal will partially restore friction, but the recovery will fall short of historical levels. Reduced-parameter removal may be appropriate, but the operator should begin planning for pavement rehabilitation. This scenario corresponds to Phase 2 of the lifecycle model.

Scenario C: Critically low friction with poor pavement condition. If friction is below or approaching the MFL and pavement condition is rated Level 1–2, rubber removal is either not viable or will be marginally effective. The primary intervention must be pavement rehabilitation. Operational restrictions (NOTAMs, wet-runway limitations) should be implemented pending rehabilitation. This scenario corresponds to Phase 3 of the lifecycle model.

The framework automates this cross-referencing logic, ensuring that the maintenance response is calibrated to both the immediate friction need and the long-term pavement reality. Without this integration, operators may repeatedly attempt rubber removal on a deteriorating surface—each attempt achieving less recovery and causing more damage—until the Phase 3 crisis point is reached, as occurred at the study airport.

6.4.6. Establishing the Pavement Condition Baseline

Before the framework can track pavement condition trends, a baseline assessment must be established. For the study airport Runway X/Y, the recommended baseline assessment would include:

1. **Visual distress survey:** comprehensive photographic documentation of surface condition at 50-metre intervals along the touchdown zones, mid-section, and recovery zones, with distress identification and severity rating.
2. **Texture depth measurement:** sand-patch tests or laser profiling at representative locations across all zones, establishing the current macrotexture depth and comparing it to the design specification for the asphalt surface course.
3. **Core sampling (if feasible):** extraction and laboratory testing of surface course cores from the RWY Y touchdown zone (heavily maintained) and a control section (lightly maintained) to quantify binder content, void structure, and aggregate condition differences.
4. **Post-removal friction benchmark:** the next rubber removal event should be documented with pre- and post-removal friction at 50-metre intervals across all zones and offsets, establishing the current "friction ceiling" of the pavement.

This baseline, once established, provides the reference point against which all future pavement condition changes are evaluated.

6.5. Component 4: Maintenance Decision Logic

6.5.1. Decision Tree with Quantified Thresholds

The maintenance decision logic integrates inputs from all three monitoring components into a structured decision tree with three primary branches:

Branch 1: Monitor. Conditions: current friction above MPL in all zones; degradation rate within historical norms; pavement condition Level 3 or above; cumulative traffic below trigger threshold. Action: continue routine monitoring; next friction test at scheduled interval.

Branch 2: Schedule Rubber Removal. Conditions: friction approaching MPL (projected breach within 60 days) OR cumulative traffic exceeds trigger threshold OR any zone below MPL but above MFL. Action: schedule rubber removal within 30 days; select technique and parameters based on pavement condition; coordinate with operations for closure window.

Branch 3: Rehabilitate. Conditions: pavement condition at Level 2 or below OR post-removal recovery trend declining below MPL OR rubber removal cannot restore friction above MPL. Action: initiate pavement engineering assessment; schedule surface treatment or resurfacing; manage friction risk with operational restrictions (NOTAMs, reduced operations in wet conditions) pending rehabilitation.

6.5.2. Decision Matrix

Table 6-2 Decision Matrix – Method Selection

Current Friction	Trend	Pavement Condition	Recommended Action	Priority
Above MPL, stable	Slow decline	Level 4–5	Continue monitoring	Routine
Above MPL, declining	MPL breach in <60 days	Level 3–5	Enhanced monitoring; plan removal	Elevated
Between MPL and MFL	Actively declining	Level 3–5	Schedule removal within 30 days	High
Between MPL and MFL	Actively declining	Level 1–2	Assess for rehabilitation; restricted removal only	Critical
Below MFL	—	Level 3–5	Immediate removal; issue NOTAM	Emergency

Below MFL	—	Level 1–2	NOTAM; operational restrictions; emergency rehabilitation	Crisis
Post-removal, above DOL	Recovery successful	Any	Resume monitoring; update model	Routine
Post-removal, below MPL	Incomplete recovery	Any	Pavement assessment; rehabilitation evaluation	High

6.5.3. Timing Optimisation

When rubber removal is recommended, the decision logic identifies the optimal closure window by cross-referencing:

- The urgency of the maintenance need (days to MFL breach)
- The seasonal traffic forecast (avoiding peak periods if possible)
- The operational feasibility of runway closure (alternate runway capacity)
- The cost implications of different timing options

At the study airport, the optimal maintenance windows would typically be May (pre-Hajj) and late September (post-lower-season, pre-Umrah escalation). The framework calculates whether friction headroom is sufficient to delay maintenance to the next optimal window or whether earlier intervention is required.

6.5.4. Technique Selection

Based on the pavement condition score, the framework recommends appropriate removal parameters:

Table 6-3 Decision Matrix – Implementation Prioritization

Pavement Level	Recommended Technique	Max Water Pressure	Passes	Notes
5 (Excellent)	Standard UHP water blast	40,000 psi	2–3	Full treatment
4 (Good)	Standard UHP water blast	30,000 psi	2	Standard parameters
3 (Fair)	Modified UHP water blast	20,000 psi	1–2	Targeted zones only
2 (Poor)	Chemical removal or low-pressure water	10,000 psi	1	Minimum intervention; engineer approval required
1 (Critical)	No rubber removal	—	—	Proceed directly to resurfacing

6.5.5. Cost-Benefit Analysis Integration

Each maintenance decision should be informed by an approximate cost-benefit analysis, even if precise quantification is not available. The framework incorporates a qualitative cost-benefit assessment as follows:

Benefits of rubber removal:

- Friction restoration (quantified from historical recovery data for the specific runway section)
- Safety margin improvement (reduced probability of friction-related incidents)
- Regulatory compliance restoration (elimination of below-MFL conditions)
- NOTAM cancellation (improved operational reputation)

Costs of rubber removal:

- Direct cost (~7 million SAR per event at the study airport)
- Runway closure cost (7–10 days of degraded operational capacity)
- Pavement damage cost (incremental reduction in friction-functional life, estimated from post-removal recovery trend)
- Scheduling coordination cost (airline rebooking, ATC reconfiguration)

Decision heuristic: Rubber removal should be performed when the expected friction recovery exceeds 0.05μ and the pavement condition score is Level 3 or above. When expected recovery falls below 0.05μ or the pavement is at Level 2, the cost-benefit balance shifts toward deferring removal and initiating rehabilitation planning.

This heuristic is calibrated from the study airport data: Event 3 achieved $+0.06\mu$ recovery on a deteriorating pavement (approaching Level 2), representing the marginal threshold below which the intervention's costs increasingly outweigh its benefits.

6.6.Component 5: Feedback and Calibration

6.6.1. Post-Maintenance Verification

After every rubber removal event, a friction test is conducted on the last day of the operation (consistent with current the study airport practice). The results are entered into the framework and compared against:

- Pre-removal friction levels (to quantify recovery)
- Historical post-removal levels for the same section (to track pavement health)
- The framework's predicted recovery (to calibrate the model)

6.6.2. Model Calibration

The degradation rate model is updated after each test-removal-test cycle using the new data. If the observed degradation rate differs significantly from the model's prediction, the coefficients are adjusted. Over successive cycles, the model converges toward the actual behaviour of the specific runway, incorporating the effects of local traffic patterns, climate, pavement composition, and maintenance practices.

The study airport dataset provides a strong starting point for calibration: six non-removal degradation periods with known traffic counts and friction measurements. These six data points establish the initial degradation rate function, with uncertainty ranges that narrow as additional data accumulate.

6.6.3. Performance Metrics

The framework tracks the following performance metrics over time:

- **Mean time between MPL breaches:** should increase as maintenance becomes better timed

- **Post-removal friction recovery:** should stabilise (decline indicates pavement deterioration)
- **Prediction accuracy:** projected versus actual MPL breach dates
- **NOTAM frequency:** "slippery when wet" NOTAMs should decrease
- **Unplanned maintenance events:** should decrease as predictive scheduling improves

6.7.Implementation Requirements

6.7.1. Data Systems

The framework requires a digital platform capable of:

- Automated ingestion of CFME test data from the a certified ASFT vehicle
- Integration with ATMS for daily landing counts and aircraft type data
- Maintenance event logging with structured fields (technique, parameters, duration, outcomes)
- Computational algorithms for degradation rate, threshold projection, and decision matrix
- Dashboard reporting for operational decision-makers

For initial deployment, these functions can be replicated using spreadsheet-based tools (e.g., Microsoft Excel with macros) that mirror the analytical algorithms. A dedicated software platform would be justified once the framework demonstrates operational value over two to three annual cycles.

6.7.2. Personnel Training

Implementation requires training across three personnel categories:

- **CFME operators:** data recording protocols; anomaly identification during testing
- **Pavement engineers and maintenance planners:** interpretation of trend data; use of decision matrix; pavement condition scoring
- **Safety managers and operations managers:** understanding of predictive outputs; integration with SMS hazard assessments; NOTAM decision criteria

Training should be integrated into the aerodrome's existing SMS training curriculum, with annual refresher modules.

6.7.3. Organisational Change

The transition from reactive to predictive maintenance requires a fundamental cultural shift. Key organisational changes include:

- **Treating friction data as a time series**, not a set of independent snapshots
- **Integrating traffic data** into maintenance planning, which may require new data-sharing protocols between ATC and maintenance departments
- **Establishing cross-departmental planning processes** between pavement engineering, operations, and safety for maintenance scheduling
- **Committing to the data discipline** the framework requires—consistent recording, standardised formats, timely entry

6.7.4. Integration with Safety Management System (SMS)

The framework's risk assessment outputs—particularly projected time-to-MFL and pavement condition flags—should feed directly into the aerodrome's SMS hazard register and risk assessment processes, as required under ICAO Annex 19 and GACA GACAR Part 139. This integration ensures that friction management decisions are contextualised within the airport's overall safety risk profile.

6.7.5. Phased Implementation Roadmap

Table 6-4 Phased Implementation Roadmap

Phase	Timeline	Activities	Deliverables
1: Foundation	Months 1–3	Establish data systems; compile historical data; train key personnel	Data repository; baseline degradation model
2: Monitoring	Months 4–9	Deploy traffic counter; conduct quarterly friction tests; perform	Calibrated degradation rates; seasonal traffic model

		pavement condition scoring	
3: Prediction	Months 10–15	Enable threshold projections; test decision matrix against historical data; shadow current decisions	Validated predictive model; comparison report
4: Full deployment	Months 16+	Use framework to drive maintenance scheduling; track performance metrics; continuous calibration	Operational decision-support system

6.7.6. Estimated Implementation Costs

While a detailed cost analysis beyond the scope of this study, approximate cost ranges for each implementation phase can be estimated based on industry benchmarks:

Table 6-5 Implementation Cost Estimation

Component	Estimated Cost (SAR)	Timeframe
Data management system (basic spreadsheet)	50,000–100,000	Phase 1
Data management system (dedicated software)	500,000–1,500,000	Phase 3–4
ATMS integration for traffic data feed	200,000–500,000	Phase 2
Personnel training programme	100,000–200,000	Phase 1–2

Pavement condition baseline assessment	300,000–600,000	Phase 1
Additional friction tests (quarterly)	150,000–300,000/year	Ongoing
Framework maintenance and calibration	100,000–200,000/year	Ongoing

The total initial investment of approximately 1–3 million SAR is modest compared to the cost of a single rubber removal event (7 million SAR) and trivial compared to the cost of premature resurfacing (40–80 million SAR). If the framework defers one rubber removal event or extends the resurfacing interval by one year, it pays for itself several times over.

6.7.7. Risk Management During Transition

The transition from reactive to predictive maintenance introduces a period of dual-system operation during which the existing reactive protocols continue alongside the new predictive capabilities. During this transition:

- **The reactive system serves as the safety net.** Regulatory-mandated friction testing and threshold-based assessment continue unchanged. The predictive system operates in parallel, generating forecasts that are compared against actual outcomes.
- **Discrepancies between prediction and reality are learning opportunities.** When the predictive model's forecast diverges from the actual friction measured at the next test, the discrepancy is analysed, root causes are identified (traffic variation, environmental effects, measurement anomalies), and the model is recalibrated.
- **The transition to predictive-driven decisions is gradual.** Initially, the predictive system's recommendations are advisory only—the reactive system drives decisions. As the predictive system demonstrates accuracy over two to three cycles, its recommendations are progressively weighted more heavily in

the decision process, eventually becoming the primary driver with the reactive system serving as a validation check.

This phased transition minimises risk by ensuring that the proven (if suboptimal) reactive system remains operational throughout the transition, while the predictive system builds its track record and earns institutional trust.

6.8.Expected Benefits

6.8.1. Safety Improvement

The framework's primary benefit is improved safety margins. By projecting threshold breaches and triggering early intervention, the framework prevents friction from reaching critically low levels between measurement events. The study airport data demonstrate that the reactive approach allowed friction to reach 0.27μ —nearly half the MFL. A predictive framework, by triggering action when friction approaches the MPL, would maintain minimum zone-specific friction above 0.50μ at all times.

6.8.2. Cost Optimisation

Cost benefits derive from multiple sources:

- **Reduced emergency mobilisations:** planned maintenance avoids premium scheduling costs
- **Less aggressive removal:** earlier intervention on lighter contamination reduces per-event pavement damage
- **Extended pavement life:** less damage per cycle extends the interval between resurfacing (estimated at 2–5 additional years, based on the Phase 2 to Phase 3 transition rate observed at the study airport)
- **Reduced NOTAM frequency:** fewer "slippery when wet" NOTAMs reduce airline delay costs and improve the airport's operational reputation

At the study airport's rubber removal cost of approximately 7 million SAR per event, extending the pavement life by even one full rubber removal cycle (avoiding one of the six annual removals that would be required under ICAO compliance) saves 7 million SAR directly, plus the avoided pavement damage extends the life of the surface layer.

6.8.3. Extended Pavement Life

The framework's most significant long-term benefit is the deferral of major rehabilitation. Resurfacing a 4,335-metre runway is a multi-week project costing tens of millions of SAR, with significant operational disruption. By optimising rubber removal timing and technique, the framework extends the pavement's friction-functional life—the period during which rubber removal can effectively maintain friction above the MPL. Based on the study airport Phase 2 transition rate, optimised maintenance could extend the friction-functional life by an estimated 20–30%, deferring the capital expenditure for resurfacing by several years.

6.8.4. Regulatory Compliance

By automatically tracking the ICAO frequency brackets and triggering friction surveys and rubber removal at the recommended intervals, the framework eliminates the compliance gap identified in Section 5.9. The framework's documentation capability also provides an auditable record of monitoring and maintenance activities, supporting the aerodrome's certification and inspection requirements under GACA GACAR Part 139.

Chapter 7 CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of Key Findings

This study investigated the interrelationships between air traffic characteristics, runway friction performance, rubber removal practices, and pavement surface condition at The study airport, a major international airport in Saudi Arabia,, over a three-year period (February 2023 to January 2026). The study analysed ten friction tests, three rubber removal events (plus one prevented event), and 28 months of air traffic data from Runway X/Y, employing a quantitative documentary analytical approach to develop an integrated decision-support framework for optimising runway friction maintenance. The following sections summarise the key findings organised by research objective.

7.1.1. Findings Related to Research Objective 1: Traffic–Friction Relationship

The analysis confirmed a direct, quantifiable relationship between cumulative air traffic and runway friction degradation:

1. **Directional asymmetry proportional to traffic load.** RWY Y, which receives approximately 65% of all landings (~1,806 per month), consistently exhibited lower friction than RWY X (~34% of traffic, ~957 per month) across all ten surveys and all three lateral offsets. In the January 2026 survey, RWY Y 6-metre average was 0.61μ compared to RWY X 6-metre average of 0.66μ .
2. **Quantified degradation rates.** Friction declined at -0.006μ per 1,000 RWY Y landings during Phase 1 (2023), accelerating to -0.014μ per 1,000 landings during Phase 2 (2024)—a 133% increase.
3. **Seasonal acceleration.** The steepest absolute decline (-0.17μ over five months) occurred during the Hajj build-up period of early 2024, when monthly RWY Y landings exceeded 2,000.
4. **Lateral concentration.** The 6-metre offset from the runway centreline consistently recorded the lowest friction (0.61μ average in January 2026), corresponding to the main landing gear track position of narrow-body aircraft, the predominant type operating at the study airport.

5. **Mass-based loading.** Weight-based analysis placed RWY Y in a more demanding ICAO maintenance bracket (rubber removal every 4 months) than landing-count analysis (every 6 months), indicating that the aircraft mix includes a significant heavy-body component that increases rubber deposition beyond what landing counts alone suggest.

7.1.2. Findings Related to Research Objective 2: Rubber Removal Impact on Pavement

The longitudinal data across three rubber removal events provided direct evidence of cumulative pavement degradation:

1. **Diminishing recovery.** Post-removal friction declined from 0.89μ (Event 2, January 2024) to 0.76μ (Event 3, April 2025)—a 14.6% reduction in maximum achievable friction.
2. **Phase 3 pavement failure.** By October 2025, the pavement had deteriorated to the point where rubber removal could not be performed without further damaging the surface, establishing the existence of a maintenance-incapacity threshold not previously documented at a Saudi aerodrome.
3. **Compounding degradation cycle.** The inability to remove rubber created a self-reinforcing cycle: pavement deterioration prevented rubber removal, which allowed rubber to continue accumulating, which further reduced friction—driving the runway toward safety-critical conditions.
4. **Three-phase lifecycle model.** The data support a pavement friction lifecycle with three distinct phases: Phase 1 (Healthy, 2023)—full recovery after removal; Phase 2 (Accelerated Degradation, 2024)—doubled degradation rate, diminished recovery; Phase 3 (Structural Deterioration, 2025–2026)—maintenance capability lost.

7.1.3. Findings Related to Research Objective 3: Reactive versus Predictive Maintenance

The case study provides compelling evidence of the reactive approach's limitations:

1. **Delayed detection.** Under the reactive regime, friction reached 0.27μ in localised zones (46% below MFL) before being identified—indicating that the monitoring interval was too long for the prevailing degradation rate.

2. **Compliance gap.** Actual rubber removal frequency (~annually) was approximately half the ICAO landing-based recommendation (semi-annually) and one-third of the weight-based recommendation (every 4 months), contributing to the accelerated degradation observed.
3. **Feasibility of prediction.** The degradation rates calculated from historical data (-0.006 to -0.014μ per 1,000 landings) are sufficiently stable within each pavement phase to enable reliable short-term projection of threshold breach dates, demonstrating that predictive maintenance is technically feasible with existing data.
4. **Cost structure favours prediction.** Earlier, planned intervention on lighter contamination would require less aggressive treatment, cause less pavement damage, and avoid the emergency logistics premium—generating savings in direct maintenance costs, operational disruption, and deferred rehabilitation.

7.1.4. Findings Related to Research Objective 4: Decision-Support Framework

The integrated five-component framework developed in Chapter 6 represents the primary deliverable of this research. Its distinctive features include:

1. **Multi-source data integration.** The framework unifies traffic monitoring, friction trend analysis, pavement condition assessment, maintenance decision logic, and feedback calibration into a single analytical workflow—addressing a gap in the existing literature where these elements are treated in isolation.
2. **Pavement viability gating.** The framework introduces a mandatory pavement condition assessment before any rubber removal is scheduled—a feature absent from current ICAO and GACA guidance that directly addresses the Phase 3 failure scenario observed at the study airport.
3. **Predictive threshold projection.** The framework projects time-to-MPL and time-to-MFL for each zone, enabling proactive scheduling that maintains friction above safety thresholds.
4. **Adaptive calibration.** The feedback loop ensures that the framework's predictive models improve with each maintenance cycle, converging toward the actual behaviour of the specific runway.

7.2. Practical Implications

7.2.1. For Airport Operators

The findings carry immediate operational implications for airport operators, particularly those managing high-traffic runways in extreme climates:

- **Zone-specific friction analysis essential.** Aggregate friction reporting masks critically deficient touchdown zones. Operators must implement 50-metre or 100-metre interval analysis with separate evaluation of each functional zone and lateral offset.
- **Traffic data must inform maintenance scheduling.** The directional asymmetry and seasonal patterns observed at the study airport demonstrate that friction maintenance needs are not uniform across time or space. Landing counts, aircraft type data, and seasonal traffic forecasts should drive monitoring and maintenance frequencies.
- **Pavement condition must be assessed before rubber removal.** The study airport experience demonstrates the catastrophic consequence of performing (or being unable to perform) rubber removal on a deteriorated surface. A pavement viability assessment should precede every removal decision.
- **Post-removal recovery must be tracked longitudinally.** A declining trend in post-removal friction is the earliest indicator of approaching Phase 3 and should trigger pavement engineering evaluation well before maintenance capability is lost.

7.2.2. For Maintenance Planners

- **Pre-season rubber removal is superior to post-season.** Scheduling removal before anticipated traffic surges (pre-Hajj, pre-Umrah high season) provides maximum friction headroom during the periods of greatest operational demand highest rubber deposition.
- **Lighter, more frequent removal is preferable to heavy, infrequent removal.** More frequent interventions with reduced water pressure and fewer passes achieve adequate friction restoration while minimising cumulative pavement damage.

- **Closure windows should be planned months in advance.** The 7–10 day closure requirement makes ad hoc scheduling extremely disruptive. Predictive capability enables maintenance to be integrated into annual operational planning.

7.2.3. For Safety Managers

- **Below-MFL conditions may exist between routine tests.** The degradation rates observed at the study airport mean that friction in the most critical zones can cross the MFL within 2–4 months of a satisfactory test. Safety managers should consider supplementary testing during high-traffic periods and after any operational anomaly (e.g., pilot reports of reduced braking action).
- **NOTAM decisions should incorporate spatial data.** A NOTAM triggered by a below-MFL average may not adequately communicate the specific location and severity of the friction deficiency. Spatial information (which touchdown zone, which offset) should be included in operational communications to pilots.

7.2.4. For Pavement Engineers

The study's findings have specific implications for the pavement engineering profession:

- **Design for maintainability.** Runway surface course designs should explicitly consider the pavement's expected rubber removal frequency and the associated cumulative damage. Surface courses with higher resistance to high-pressure water erosion—such as those incorporating hard, angular aggregates with high polishing resistance and polymer-modified binders with superior adhesion—would extend the friction-functional life.
- **Specify removal-tolerant aggregate.** The aggregate type used in the surface course directly affects the pavement's vulnerability to rubber removal damage. Aggregates with high micro-Deval abrasion resistance and low polished stone value loss will retain their microtexture through more removal cycles. For Gulf-region airports, research into locally available aggregates with these characteristics would be valuable.

- **Include rubber removal life in pavement design life.** Current pavement design methodologies (FAA AC 150/5320-6F, ICAO Annex 14) define design life primarily in structural terms (load repetitions to fatigue failure or rutting limit). A parallel friction-functional life—the number of rubber removal cycles the surface can sustain before post-removal friction falls below the MPL—should be estimated at the design stage and incorporated into the lifecycle cost analysis.
- **Evaluate surface treatment options for Phase 2 pavements.** When a runway surface enters Phase 2 (declining post-removal recovery), intermediate interventions short of full resurfacing—such as micro-surfacing, slurry seal, or fog seal—may restore surface texture and extend the friction-functional life at a fraction of the resurfacing cost. Research into the effectiveness of these treatments on rubber-removal-degraded airport pavements in Gulf climates would be beneficial.

7.3.Recommendations

7.3.1. Recommendations for the study airport

Based on the findings and analysis of this study, the following specific, actionable recommendations are offered for the study airport:

1. **Immediate pavement rehabilitation assessment.** Commission a detailed pavement condition assessment of the Runway X/Y asphalt surface, particularly in the RWY Y touchdown zone (0–800 metres from threshold), to determine the extent of surface deterioration and the feasibility of surface treatment versus full resurfacing. Given the current inability to perform rubber removal, this assessment is urgent.
2. **Interim operational risk mitigation.** Until pavement rehabilitation restores maintenance capability, issue and maintain a NOTAM advising that Runway X/Y may be slippery when wet, with specific reference to the RWY Y touchdown zone. Consider operational restrictions (e.g., reduced maximum crosswind limits when wet) during this interim period.
3. **Implement traffic-based monitoring triggers.** Establish cumulative landing counters for each runway end and trigger enhanced friction monitoring when

cumulative RWY Y landings exceed 8,000 since the last rubber removal (approximately 4.4 months at average traffic).

4. **Adopt semi-annual rubber removal schedule.** Align rubber removal frequency with the ICAO landing-based recommendation of every 6 months, with removal events timed to pre-Hajj (May) and pre-Umrah (September/October) windows. Evaluate the mass-based interval (every 4 months) if the fleet mix becomes heavier.
5. **Implement the decision-support framework.** Deploy the five-component framework described in Chapter 6 as a pilot project on Runway X/Y, beginning with the traffic monitoring and friction trend analysis components. Use the first two annual cycles to calibrate the degradation rate models and establish decision thresholds.
6. **Establish a data management system.** Create a unified digital repository linking friction test data, traffic records, rubber removal logs, and pavement condition assessments. Ensure all friction data are recorded at the 50-metre interval level with zone and offset identification.
7. **Adopt zone-targeted rubber removal.** Focus intensive rubber removal on the 3–9 metre band from the runway centreline in the identified touchdown zones (0–800 metres from each threshold), with lighter or no treatment for the outer sections and mid-runway zones. This targeted approach reduces total pavement surface exposed to removal damage.
8. **Track post-removal recovery systematically.** After every rubber removal event, record the post-removal friction for each zone and offset, and compare it to historical post-removal levels. A decline of more than 0.05μ from the best historical recovery should trigger an immediate pavement condition assessment.

7.3.2. Recommendations for Similar Aerodromes

1. Aerodromes with seasonal traffic surges—such as other Saudi airports serving Hajj/Umrah traffic (Jeddah KAIA, Riyadh KKIA) or airports with seasonal

tourism peaks—should implement pre-season rubber removal and enhanced monitoring during peak periods.

2. Aerodromes operating in extreme desert climates should account for the accelerated pavement aging effects of high temperatures, UV radiation, and thermal cycling when planning rubber removal frequencies and technique selection. Higher ambient temperatures during rubber removal may require parameter adjustment.
3. All aerodromes should transition from aggregate-level friction reporting to zone-specific, interval-level analysis that identifies localised deficiencies masked by averaged metrics.
4. Single-runway airports should develop contingency protocols for maintaining friction during the 7–10 day rubber removal closure, including night-only operations, capacity restrictions, or phased (half-runway) treatment approaches.

7.3.3. Recommendations for GACA and Regulatory Authorities

1. **Supplement threshold-based requirements with trend guidance.** GACA should consider issuing an Advisory Circular providing guidance on friction trend analysis and predictive maintenance approaches, complementing the existing threshold-based requirements in GACAR Part 139.
2. **Mandate pavement condition assessment before rubber removal.** Regulatory guidance should require a pavement condition evaluation as a precondition for rubber removal scheduling, establishing minimum surface condition standards below which removal should not be performed.
3. **Require zone-specific friction reporting.** Amend GACAR Part 139 reporting requirements to mandate zone-specific friction data (by touchdown zone and offset) in addition to the current portion-based averages, ensuring that localised deficiencies are captured in the regulatory record.
4. **Adjust monitoring frequency for seasonal traffic.** Require enhanced friction monitoring frequency during identified peak traffic periods (e.g., monthly testing during Hajj season) rather than maintaining a fixed schedule that may be inadequate during traffic surges.

5. **Mandate post-removal recovery tracking.** Require aerodromes to maintain longitudinal records of post-removal friction recovery, with a regulatory flag for investigation when recovery declines by more than 10% from historical best values.

7.4. Contribution to Knowledge

This study makes several contributions to the academic and professional knowledge base:

Theoretical contribution: Three-phase pavement friction lifecycle model. The identification and characterisation of three distinct phases—Healthy, Accelerated Degradation, and Structural Deterioration—in the friction-functional lifecycle of an asphalt runway surface provides a new conceptual framework for understanding long-term friction management dynamics. The Phase 3 concept of maintenance incapacity, where the pavement can no longer sustain the maintenance designed to restore its function, is a novel contribution with implications for pavement management theory.

Methodological contribution: Integrated multi-source analysis. The study demonstrates the analytical value of integrating friction test data, air traffic records, rubber removal logs, and pavement condition observations into a unified analysis framework. This multi-source approach reveals relationships—such as the traffic-normalised degradation rate acceleration and the diminishing post-removal recovery trend—that would be invisible from any single data source alone.

Practical contribution: Decision-support framework with pavement gating. The five-component framework, particularly the pavement viability gating criterion, fills a gap in the existing runway friction management literature. The framework is designed for practical implementation and can be deployed at operational aerodromes with existing data streams.

Contextual contribution: Saudi aerodrome empirical data. The study provides the first detailed, longitudinal analysis of runway friction performance, traffic loading, and maintenance outcomes at a major Saudi aerodrome, contributing to the limited body of published research on runway friction management in the Gulf region's unique climatic and operational context.

Operational contribution: Evidence base for predictive maintenance in aviation.

While predictive maintenance is well established in manufacturing, fleet management, and power generation, its application to runway friction management remains nascent. This study provides empirical evidence—from a real operational aerodrome with real traffic, real friction data, and real maintenance outcomes—that supports the transition to predictive friction maintenance. The case study demonstrates both the failure mode of reactive maintenance (Phase 3 crisis) and the feasibility of prediction (stable degradation rates within pavement phases), providing the evidence base for operational adoption.

Regional contribution: Gulf-region airport engineering. Published research on runway friction management in the Gulf Cooperation Council (GCC) region is extremely limited. This study addresses that gap by providing the first detailed analysis of friction performance, traffic loading, and maintenance outcomes at a major Saudi aerodrome operating under the region's unique conditions: extreme heat ($>45^{\circ}\text{C}$ summer), intense UV exposure, seasonal pilgrimage traffic surges, and the institutional framework of a concession-operated international airport. The findings and recommendations are directly applicable to other GCC airports and provide a basis for region-specific guidance development by GACA and the GCC Standardization Organization.

Safety contribution: Identification of the Phase 3 compounding cycle. Perhaps the most urgent practical contribution of this study is the identification and documentation of the Phase 3 compounding degradation cycle. This failure mode—where pavement deterioration prevents rubber removal, leading to rubber accumulation, leading to further friction loss, in a self-reinforcing spiral—represents a previously undocumented safety risk. By characterising this cycle and its precursors, the study enables airport operators to identify approaching Phase 3 conditions and intervene before the compounding cycle begins. The framework's pavement viability gating criterion is specifically designed to prevent this failure mode.

7.5.Limitations of the Study

The following limitations should be acknowledged:

1. **Single airport, single runway.** The study is based on data from a single runway at a single aerodrome (the study airport Runway X/Y), which limits

the generalisability of specific quantitative findings—particularly the degradation rate coefficients and phase transition thresholds—to other aerodromes with different pavement types, climates, traffic profiles, and maintenance histories.

2. **Missing traffic data periods.** Air traffic data were unavailable for five months during the study period (November 2024–April 2025 and November 2025–January 2026), requiring estimation using monthly averages. These estimations introduce uncertainty into the traffic-normalised degradation rates for the affected inter-test periods.
3. **No direct pavement condition measurements.** Pavement condition during the study was characterised through operational observations (the inability to perform rubber removal) rather than through standardised engineering measurements (PCI scoring, core sampling, deflection testing). Direct measurement data would strengthen the Phase 3 characterisation.
4. **Tyre type changes.** The CFME test equipment transitioned from a T49 tyre at 7.0 bar (Reports 10, 11) to an ASTM tyre at 7.0 bar (Reports 9, 12) and then to an ASTM tyre at 2.1 bar (Reports 1–8). These changes affect the absolute friction values recorded and introduce potential discontinuities in the longitudinal trend. While the trend direction is preserved, the magnitude of inter-test changes may be partially attributable to equipment changes rather than actual surface friction changes.
5. **No cost-benefit quantification.** While the study describes the economic logic of predictive versus reactive maintenance and provides approximate costs (7 million SAR per rubber removal event), a comprehensive lifecycle cost analysis was beyond the scope of this research. The quantified cost savings remain estimates rather than validated figures.
6. **Framework not yet validated prospectively.** The decision-support framework was developed based on analytical reasoning, literature synthesis, and retrospective case study evidence. Prospective validation—deploying the framework and comparing its recommendations and outcomes against the reactive baseline—has not yet been conducted.

7.6.Future Research Directions

This study opens several avenues for future investigation:

1. **Multi-airport study across Saudi Arabia.** Extending the analysis to multiple Saudi aerodromes—including Jeddah (KAIA), Riyadh (KKIA), and smaller regional airports—would test the generalisability of the lifecycle model and enable the development of region-specific calibration parameters. The variation in pavement types, climates, and traffic profiles across Saudi airports provides a natural experimental design for comparative analysis.
2. **Real-time friction monitoring integration.** Emerging technologies—including surface-embedded sensors, satellite imagery analysis (as explored by Aquino et al., 2026), and continuous friction monitoring vehicles—could provide higher-frequency friction data that would enhance the framework's predictive resolution. Research into the cost-effectiveness and reliability of these technologies at Gulf-region airports would be valuable.
3. **Machine learning for degradation prediction.** The framework's current prediction methodology uses linear extrapolation within each pavement phase. Machine learning approaches—random forests, gradient boosting, or recurrent neural networks—could capture non-linear interactions among traffic, environmental, and pavement variables, potentially improving prediction accuracy. The study airport dataset provides a starting point for model development, though larger multi-airport datasets would be needed for robust training.
4. **Pavement core sampling to quantify structural damage.** Extracting and testing core samples from the study airport runway—particularly from the heavily maintained RWY Y touchdown zone and the less-maintained mid-section as a control—would provide direct engineering evidence of the rubber-removal-induced surface degradation hypothesised in this study. Comparison of aggregate condition, binder content, void structure, and microtexture between zones would validate the three-phase model.
5. **Economic optimisation model.** A comprehensive lifecycle cost model integrating rubber removal costs, pavement rehabilitation costs, operational disruption costs, and safety-related risk costs would enable quantitative

optimisation of the maintenance schedule. Such a model could determine the cost-optimal rubber removal frequency and technique for a given pavement age and traffic profile, providing the economic justification for framework adoption.

6. **Rubber removal technique comparison.** Controlled experiments comparing ultra-high-pressure water blasting, chemical removal, shot blasting, and mechanical methods on matched pavement sections under Gulf climate conditions would provide the empirical data needed to optimise the framework's technique selection recommendations and quantify the pavement damage associated with each method.
7. **Digital twin integration.** The framework's data-driven architecture is well suited for integration with digital twin technology—a virtual representation of the runway pavement that continuously updates with real-time traffic, friction, and environmental data. A digital twin could enable scenario simulation (e.g., "what if Hajj traffic increases by 20%?") and automated decision recommendations, representing the next evolution of the framework concept.
8. **Environmental factor integration.** The study airport data do not fully isolate the effects of temperature, humidity, and UV exposure on friction degradation. A controlled study measuring these environmental variables alongside traffic and friction data would enable the development of climate-adjusted degradation models. The study city's extreme heat profile (summer temperatures routinely exceeding 45°C) likely accelerates both rubber softening during touchdown and post-removal oxidative aging of the exposed pavement surface—effects that would not apply to temperate-climate airports. Quantifying these effects would improve the framework's predictive accuracy for Gulf-region aerodromes.
9. **Fleet composition effects.** The current study uses aggregate traffic data without aircraft-type disaggregation. Research into the specific rubber deposition rates of different aircraft types—particularly the comparison between narrow-body (A320, B737) and wide-body (A330, B777, B787) aircraft—would enable more accurate weighted traffic metrics and more precise friction predictions. Flight data recorder analysis of touchdown

parameters (speed, sink rate, tyre pressure) could provide aircraft-type-specific deposition coefficients.

10. **Regulatory framework development.** The study's findings suggest that current ICAO guidance on friction management would benefit from formal integration of pavement condition assessment, post-removal recovery tracking, and predictive maintenance concepts. A collaborative research programme involving ICAO, national regulators (GACA, FAA, EASA), and aerodrome operators could develop updated guidance material that reflects the lifecycle model and framework concepts proposed in this study.

7.6.1. Concluding Remarks

In conclusion, this study has demonstrated through detailed empirical analysis of a three-year dataset from the study airport that runway friction management is a far more complex and consequential undertaking than the simple test-and-remove paradigm suggests. The interaction between traffic loading, rubber accumulation, friction degradation, pavement surface damage, and maintenance effectiveness creates a dynamic system that evolves through distinct lifecycle phases, each requiring different management strategies.

The reactive approach that currently predominates at the study airport—and at many aerodromes globally—is adequate during Phase 1 of the pavement lifecycle but becomes progressively less effective and ultimately counterproductive as the pavement transitions through Phase 2 and into Phase 3. The January 2026 situation at the study airport, where the runway exhibits critically low friction (minimum 0.27μ) but cannot undergo rubber removal due to pavement deterioration, represents the terminal failure mode of the reactive approach. This outcome was not inevitable—it was the predictable consequence of maintenance decisions made without adequate consideration of the cumulative impact on pavement integrity.

The integrated decision-support framework developed in this study provides a structured, data-driven alternative that anticipates friction decline, optimises maintenance timing and technique, monitors pavement health, and prevents the compounding degradation cycle that leads to Phase 3 failure. The framework is designed for practical deployment with existing data streams and can be implemented incrementally, beginning with simple traffic and friction trend monitoring and

progressing to full predictive decision support as institutional capacity and data quality develop.

The most important message of this research is that runway friction management must be understood as a lifecycle problem, not a point-in-time threshold problem. Every maintenance decision—to remove rubber or defer, to use high pressure or low, to resurface now or later—has consequences that extend years into the future. Only a framework that accounts for these long-term dynamics can optimise the safety–pavement–cost trade-off and ensure that aerodromes maintain adequate friction throughout the full lifecycle of their pavement infrastructure.

The framework is offered as both a practical tool for immediate application at the study airport and similar aerodromes, and as a foundation for continued research and development in this critical domain of aviation safety engineering. Its adoption would represent a significant step toward the proactive, data-driven infrastructure management that is the stated goal of both ICAO's safety management framework and GACA's regulatory vision for the Kingdom's aviation sector.

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APPENDICES

Appendix A: Technical Review Request Letter

To: Eng. Abdulhafiz Khalmurad

Projects Director

Request for Technical Review – Master's Research

Dear Eng. Abdulhafiz Khalmurad,

I hope this message finds you well.

As part of my Master's degree requirements at **Midocean University – College of Management**, I am conducting a research study titled:

"Runway Maintenance Decision Support Through Integrated Analysis of Friction Trends, Air Traffic Characteristics, and Rubber Removal Practices: An Applied Study on Saudi Airports."

Given your role as **Projects Director** and your oversight of runway and airside infrastructure works, I would highly appreciate your technical review of the **attached full research manuscript**, particularly the methodology and engineering assumptions related to runway maintenance and rubber removal operations.

Your feedback or comments would be greatly appreciated and will help strengthen the technical validity of the research.

Thank you very much for your time and support.

Best regards,

Zaid Badawi

Technical Expert Review Letter

To: Research Committee

College of Management

Midocean University

I have reviewed the research developed by **Eng. Zaid Badawi** titled:

"Runway Maintenance Decision Support Through Integrated Analysis of Friction Trends, Air Traffic Characteristics, and Rubber Removal Practices: An Applied Study on Saudi Airports."

The research addresses practical aspects of **runway pavement maintenance decision-making**, including the analysis of friction performance trends, air traffic operational characteristics, and rubber removal practices within airport environments.

As part of this review, the study methodology and technical assumptions related to **runway maintenance operations, friction performance considerations, and rubber removal practices** were examined from an operational and engineering perspective.

Based on this review, the overall research framework and methodological approach are technically reasonable and relevant to practical airside maintenance and runway management practices.

Thank you.

Eng. Abdulhafiz Khalmurad

Projects Director

Tibah Airport Operations Company

Date: 16-March-2026

Signature: 

Subject: Request for Technical Review of Master's Thesis — Runway Friction Management Decision-Support Framework

MIDOCEAN UNIVERSITY

College of Management

Department of Business Administration

**Supporting Runway Maintenance Decisions Through Integrated Analysis of
Friction Trends, Flight-Traffic Characteristics, and Rubber Removal Practices:
An Applied Study on Saudi Airports**

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Year: 2026