JORGE BRAULIO COSSÍO DURÁN

**AVALIAÇÃO DA IRREGULARIDADE LONGITUDINAL DE PAVIMENTOS
AEROPORTUÁRIOS ATRAVÉS DA RESPOSTA DINÂMICA DAS AERONAVES**

Programa de Pós-graduação em
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AEROPORTUARIOS A TRAVÉS DE LA RESPUESTA DINÁMICA DE LAS AERONAVES**

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RESUMO

DURAN, J. B. C. (2019). **Avaliação da Irregularidade Longitudinal de Pavimentos Aeroportuários Através da Resposta Dinâmica das Aeronaves**. Tese (Doutorado em Ciências) – Departamento de Engenharia de Transportes, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brasil.

Os pavimentos aeroportuários e os perfis de elevação longitudinal, em conjunto com as aeronaves, formam um sistema onde são produzidos deslocamentos verticais que podem comprometer seu desempenho. Pavimentos irregulares são geralmente responsáveis pela ocorrência de respostas dinâmicas como acelerações verticais e carregamentos no pavimento que podem danificar a aeronave, aumentar a distância de parada e dificultar a leitura dos instrumentos de navegação na cabine dos pilotos. Para abordar esse problema, os índices *International Roughness Index* (IRI) e *Boeing Bump Index* (BBI) são utilizados atualmente para quantificar a irregularidade longitudinal dos pavimentos aeroportuários e identificar seções que demandem atividades de manutenção e reabilitação (M&R). No entanto, tais índices foram desenvolvidos apenas com base nas respostas dinâmicas de um automóvel a 80 km/h às irregularidades dos pavimentos rodoviários e a partir das características físicas das irregularidades, respectivamente, sem considerar o efeito da resposta dinâmica das aeronaves. Ainda, os limites críticos atuais para IRI e BBI podem subestimar a condição real do pavimento. Esta pesquisa objetiva avaliar o efeito da irregularidade longitudinal na resposta dinâmica das aeronaves em termos de acelerações verticais na cabine dos pilotos (VACP) e no centro de gravidade (VACG) assim como os carregamentos no trem de pouso de nariz, principal e traseiro (NGPL, MGPL e RGPL, respectivamente), que podem comprometer a segurança das aeronaves e o desempenho do pavimento. O *software* ProFAA foi utilizado para calcular os dois índices e para simular as respostas de 4 aeronaves representativas operando 20 pistas de pouso e decolagem em 10 velocidades de operação variando de 20 a 200 nós (37 a 370 km/h). Comparações estatísticas e análises de regressão entre índices e respostas dinâmicas foram realizadas. Os principais resultados indicaram que VACP foi 50% maior do que VACG e que NGPL foi aproximadamente 80% maior do que MGPL. Além disso, observou-se que VACP ultrapassa 0,40 g quando o IRI está acima de 3,7 m/km e que NGPL dobra a carga estática quando o IRI está acima de 3,3 m/km. Um estudo de caso apresentado para comparar esses limites indicou que a tomada de decisão baseada na resposta dinâmica das aeronaves pode trazer diferenças significativas na quantidade e qualidade das atividades de M&R.

Palavras-chave: Pavimentos aeroportuários, irregularidade longitudinal, resposta dinâmica das aeronaves, *International Roughness Index*, *Boeing Bump Index*.

ABSTRACT

DURAN, J. B. C. (2018). **Airport Pavement Roughness Evaluation through Aircraft Dynamic Response**. PhD. Dissertation (Doctor of Philosophy) – Department of Transportation Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil.

Airport pavements and longitudinal elevation profiles, in conjunction with the aircraft, form a system where vertical displacements are produced that can compromise their performance. Rough pavements are generally responsible for the occurrence of dynamic responses such as vertical accelerations and pavement loads that affect the aircraft, increase stopping distance and difficult to read the cockpit instrumentation. To approach this problem, the International Roughness Index (IRI) and the Boeing Bump Index (BBI) are currently used to quantify airport pavement roughness and to identify sections that need maintenance and rehabilitation (M&R) activities. However, such indices were developed only based on the dynamic responses of an automobile at 80 km/h to the irregularities of road pavements, and from the physical characteristics of the irregularities, respectively, without considering the effect of the aircraft dynamic response. In addition, current critical limits for IRI and BBI can misjudge the real condition of the pavement. This research aims to evaluate the effect of airport pavement roughness on aircraft dynamic response in terms of vertical accelerations at the aircraft cockpit (VACP) and at the center of gravity (VACG), as well of dynamic loads at the nose, main and rear landing gear (NGPL, MGPL, and RGPL), which may compromise the aircraft safety and the pavement performance. The ProFAA software was used to compute both indices and to simulate the responses of 4 representative aircraft traversing 20 runway profiles at 10 operational speeds varying from 20 to 200 knots (37 to 370 km/h). Statistical comparisons and regression analyses between roughness indices and dynamic responses were carried out. Principal results indicated that VACP was 50% higher than VACG and that NGPL was approximately 80% higher than MGPL. In addition, it was observed that VACP exceeds 0.40 g when the IRI is higher than 3.7 m/km and that NGPL doubles the static load when the IRI is higher than 3.3 m/km. A case study presented to compare these limits shown that decision-making based on the dynamic response of the aircraft can bring significant differences in the number and quality of M&R activities.

Keywords: Airport pavements, pavement roughness, aircraft dynamic response, International Roughness Index, Boeing Bump Index.

RESUMEN

DURAN, J. B. C. (2018). **Evaluación de la Irregularidad Longitudinal de Pavimentos Aeroportuarios a través de la Respuesta Dinámica de las Aeronaves**. Tesis (Doctorado en Ciencias) – Departamento de Ingeniería de Transportes, Escuela de Ingeniería de São Carlos, Universidad de São Paulo, São Carlos, Brasil.

Los pavimentos aeroportuarios y los perfiles de elevación longitudinal, en conjunto con las aeronaves, forman un sistema donde se producen desplazamientos verticales que pueden comprometer su desempeño. Pavimentos irregulares son generalmente responsables por respuestas dinámicas como aceleraciones verticales y cargas en el pavimento que pueden afectar a la aeronave, aumentar la distancia de parada y dificultar la lectura de los instrumentos de navegación en la cabina de los pilotos. Para tratar este problema, los índices *International Roughness Index* (IRI) y *Boeing Bump Index* (BBI) son utilizados actualmente para cuantificar la irregularidad longitudinal de los pavimentos aeroportuarios e identificar secciones que necesitan actividades de mantenimiento y rehabilitación (M&R). Sin embargo, tales índices fueron desarrollados sólo a partir de las respuestas dinámicas de un automóvil a 80 km/h a las irregularidades de los pavimentos de carreteras y a partir de las características físicas de las irregularidades, respectivamente, sin considerar el efecto de la respuesta dinámica de las aeronaves. Asimismo, los límites críticos actuales para IRI y BBI pueden subestimar la condición real del pavimento. Esta investigación objetiva evaluar el efecto de la irregularidad longitudinal en la respuesta dinámica de las aeronaves en términos de aceleraciones verticales en la cabina de los pilotos (VACP) y en el centro de gravedad (VACG) así como de cargas en el tren de aterrizaje de nariz, principal y trasero (NGPL, MGPL y RGPL, respectivamente), que pueden comprometer la seguridad de las aeronaves y el desempeño del pavimento. El software ProFAA fue utilizado para calcular ambos índices y para simular las respuestas de 4 aeronaves representativas operando 20 pistas de aterrizaje en 10 velocidades de operación variando de 20 a 200 nudos (37 a 370 km/h). Se realizaron comparaciones estadísticas y análisis de regresión entre índices y respuestas dinámicas. Los principales resultados indicaron que VACP fue 50% mayor que VACG y que NGPL fue aproximadamente 80% mayor que MGPL. Además, se observó que VACP excede 0.40 g cuando el IRI es superior a 3.7 m/km y que NGPL dobla la carga estática cuando el IRI es superior a 3.3 m/km. Un estudio de caso presentado para comparar estos límites indicó que la toma de decisión basada en la respuesta dinámica de las aeronaves puede traer diferencias significativas en la cantidad y calidad de actividades de M&R.

Palabras clave: Pavimentos aeroportuarios, irregularidad longitudinal, respuesta dinámica de aeronaves International Roughness Index, Boeing Bump Index.

ABBREVIATIONS

AC - Asphalt Concrete

ACRP - Airport Cooperative Research Program

AGARD - Advisory Group for Aeronautical Research and Development (old)

ANAC - National Civil Aviation Agency (Brazil)

APMS - Airport pavement Management System

APR - Airport Pavement Roughness Consultants

AR&L - Auto Road & Level

ARAN - High-speed roughness profilometer

ASTM - American Society of Testing and Materials

ATRP - Airport Technology Research Program

BBI - Boeing Bump Index

CG - Center of Gravity

CRLF - Carriage Return Line Feed delimiters

CSV - Comma-separated values

DNER - National Highway Department (Brazil) - old

DNIT - National Department of Transportation Infrastructure (Brazil)

ERD - Engineering Research Division of the UMTRI

FAA - Federal Aviation Administration

FHWA - Federal Highway Administration

FOD - Foreign Object Debris

GAG - Ground-Air-Ground cycles

GEIPOT - Brazilian Transportation Planning Company (old)

GQC - Golden Quarter-car model

IBM-SPSS - International Business Machines Corporation

IBRD - International Bank for Reconstruction and Development

ICAO - International Civil Aviation Organization

IPR - Road Research Institute of DNIT (Brazil)

IRI - International Roughness Index

IRRE - International Road Roughness Experiment

ISO - International Organization for Standardization

LCPC - French Bridge and Pavement Laboratory

LTPP - Long-Term Pavement Performance database

M&R - Maintenance and Rehabilitation

MAX - Maximum or peak values

MGPL - Main Gear Pavement Loads

MTOW - Maximum Take-Off Weight

NACA - National Advisory Committee for Aeronautics (old NASA)

NASA - National Aeronautics and Space Administration

NCHRP - National Cooperative Highway Research Program

NDT - Nondestructive Pavement Testing

NGPL - Nose Gear Pavement Loads

OECD - Organization for Economic Co-operation and Development

PCC - Portland Cement Concrete

PDFs - Probability Distribution Functions

PI - Profile Index

PPMC - Pearson Product Moment Correlation

ProFAA - Profile Federal Aviation Administration software

RCI - Riding Comfort Index

RGPL - Rear Gear Pavement Loads

RMS - Root Mean Square

RTRRMs - Response Type Road Roughness Meters

SEB - Single Event Bump

SPSS - Statistical Package for the Social Sciences

TRA - US Tire and Rim Association

TRRL - British Transport and Road Research Laboratory

UMTRI - University of Michigan Transportation Research Institute

USACE - US Army Corps of Engineers

VACG - Vertical Accelerations at the Center of Gravity

VACP - Vertical Accelerations at the Cockpit

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1 INTRODUCTION

1.1 CONTEXTUALIZATION OF THE RESEARCH AND PROBLEM STATEMENT

Airport pavements are constructed to provide adequate support for the loads imposed by airplanes and to produce a firm, stable, smooth, all-year, all-weather surface free of debris or other particles that may be blown or picked up by propeller wash or jet blast. However, pavements are also subject to deterioration and to the occurrence of several distresses due to dynamic loading, environmental effects, quality of construction materials, and efficiency of the construction process, among others.

One of the most commonly distresses in airport pavements are those related to functional factors such as raveling, weathering, and Jet-Blast (including Foreign Object Debris – FOD as a consequence of these distresses) as well as to structural factors such as rutting, depressions, and the lack of smoothness or roughness.

Roughness can be defined as the longitudinal deviations of a pavement surface from a true planar surface with characteristic dimensions that affect aircraft dynamics, ride quality and dynamic pavement load, and can cause discomfort, excessive vibrations in the aircraft cockpit, and potential danger both to the aircraft and its passengers.

According to FAA (2009), the highway industry defines pavement roughness in terms of the ride quality experienced by a passenger. Automotive manufacturers design suspension systems to reduce the impact of common surface irregularities and improve overall ride quality. However, the primary purpose of an airplane suspension system is to absorb the energy expended during landing. Airplane suspension systems have less capacity to dampen the impact of surface irregularities due to the magnitude of the energy that must be addressed during landing. Thus, airport pavement roughness should be defined in terms of fatigue on aircraft components (increase stress and wear) and/ or other factors which may impair the safe operation of the aircraft (cockpit vibrations, excessive g-forces, etc.).

Unlike highways, airport pavement roughness is not defined by perceived ride quality or passenger discomfort. Although important, passenger discomfort due to pavement surface irregularities is often not a significant issue since the degree of discomfort is small and the time of exposure is limited to a few seconds. Further, passenger discomfort often occurs during takeoff and landing operations when engine noise, aerodynamic noise, and/or horizontal acceleration or deceleration can distract the passengers.

In general, rough pavements result in high dynamic loading for the aircraft and the pavement which reduce the useful life of both. To adequately evaluate an airport pavement for roughness, the aircraft response to the pavement elevation profile of that pavement must be known. This response is a function of the aircraft type, its operational speed and the geometry of the axle and tires. The speed at which a rough area is encountered is particularly important. On a runway, an aircraft could traverse any pavement section at any speed. It could be a takeoff, landing or rejected takeoff from either end of the runway. Consequently, aircraft response to any pavement section must be known at all speeds in order to fully evaluate it for roughness content.

Furthermore, pavement roughness is also an important indicator for Airport Pavement Management Systems (APMS). The study of pavement roughness provides valuable information for airport managers and engineers and allows to identifying pavement sections with excessive levels of roughness that are capable to impair the safety of ground operations, cause damage, or increase structural fatigue to an aircraft. For this reason, as the pavement infrastructure aged or deteriorated and roughness becomes to be critical, a systematic approach to determining Maintenance and Rehabilitation (M&R) needs and priorities is necessary. To attend this demand, airport pavement engineers, managers, and administrators should look for an APMS so that pavements be managed, not simply maintained.

In the airport pavement management field, efforts have been focused on identify and quantify pavement roughness. In most airfields, roughness is often characterized by the International Roughness Index (IRI) developed by The World Bank for highway pavements – and also recommended by the National Civil Aviation Agency in Brazil (ANAC, 2019) – and by the Boeing Bump Index (BBI) developed by

The Boeing Company and also suggested by the Federal Aviation Administration (FAA).

These indices measure a pavement elevation profile accordingly with critical limits for excessive level of roughness. However, these indices are based on specific mathematical models that do not consider the effect of aircraft dynamic response, such as verticals accelerations generated at the aircraft cockpit and center of gravity, as well as pavement loads occurring at the nose and main landing gear and even at the rear landing gear, an additional landing gear that generally complements the main landing gear of large aircraft such as the B-747. As a consequence, current critical limits for roughness can misjudge the real pavement condition in terms of excessive aircraft dynamic responses and, therefore, indicate a large number of unnecessary pavement rehabilitation activities.

Evidently, there is a need to understand the behavior of vertical accelerations and pavement loads when commercial aircraft traverses a rough runway at different operational speeds and also it is necessary to calibrate or adjust those current limits.

1.2 APPROACH OF THE PROBLEM

Analyses of aircraft dynamic responses were conducted in this research in order to investigate the airport pavement roughness behavior from an aircraft safety and pavement performance point of view. In this context, response simulations were performed assuming that the aircraft is a rigid body that despises the influence of aerodynamic forces. Moreover, the operational speeds selected in this research for the simulations are discrete along the pavement elevation profile. This means that the aircraft traverses the runway at a constant speed in each simulation, despising landing and takeoff effects.

This research is based on the hypothesis that current critical limits imposed by traditional pavement roughness indices such as IRI and BBI, can be adjusted to take into account the effect of vertical accelerations at the aircraft cockpit and center of gravity and dynamic pavement loads at the nose and main landing gears as well as at the rear landing gear of a large commercial aircraft. The adoption of such approach was motivated by the evident need for new standards to assess airport pavement roughness based on aircraft dynamic responses.

1.3 OBJECTIVES

The main objective of this research is to evaluate the effect of airport pavement roughness on aircraft dynamic response in terms of vertical accelerations and dynamic loads, which may compromise the aircraft safety and the pavement performance. In order to achieve this objective, the following research tasks are conducted:

- 1) To compare currently pavement roughness indices IRI and BBI;
- 2) To compare vertical accelerations at the aircraft cockpit with vertical accelerations at the center of gravity, as well as between pavement loads at the nose and main landing gears and also at a rear landing gear, through the simulation of a variety of representative commercial aircraft traversing several pavement elevation profiles at different discrete operational speeds;
- 3) To correlate pavement roughness indices with aircraft dynamic responses by operational speed and aircraft weight;
- 4) To identify critical limits based on excessive response and propose alternative classifications for airport pavement roughness evaluation based on critical aircraft dynamic responses.

1.4 DISSERTATION STRUCTURE

This dissertation is organized as follows:

- Chapter 1 contextualizes the study and presents the statement and approach of the problem, the main and secondary objectives and the structure of the dissertation;
- Chapter 2 summarizes the literature review on pavement roughness concepts, International Roughness Index, Boeing Bump Index, aircraft dynamic responses and ProFAA software;
- Chapter 3 presents the elevation profile data and describes the criterion used to carry out the response simulations and to compute the indices;
- Chapter 4 discusses the data analysis and findings of the study. This chapter comprises the following sections: IRI vs. BBI; cockpit accelerations vs. center of gravity accelerations; nose gear pavement loads vs. main and rear gear pavement loads; accelerations and loads vs. speed and vs. pavement

roughness indices; statistical comparisons in the form of Pearson's correlations and regression analyses; and alternative airport pavement roughness classifications;

- Chapter 5 presents a Case study that exemplify the implementation of the alternative airport pavement roughness classifications for an airport network comprised of nine medium and large airport runways of asphalt concrete which are currently in operation;
- Chapter 6 lists the conclusions of the research and presents some recommendations for further studies.

2 LITERATURE REVIEW

2.1 PAVEMENT ROUGHNESS

2.1.1 Background and Concepts

Pavement roughness has been a concerning issue over the years. As cited by Hveem (1960), ever since roads and highways have been constructed, the people who use them have been keenly aware of the relative degrees of comfort or discomfort experienced in traveling. The evidence that remains today from the paved roads of the Roman Empire suggest that roughness must have been a concern for chariot travel (Figure 1). Even in the 1800s, high-speed travel in this country by stagecoach had a rigorous reputation directly resulting from the roughness of the roadway.

Figure 1 Photograph of an early Roman road (source: Romanobritain, 2018)

In the case of airport pavements, concerns about roughness gained importance since World War II because of the attacks on the Air Force Bases which aimed to avoid air counterattack and weaken supply chains. The attacks mainly affected runways and aprons. This forced engineers to execute pavement rehabilitations such as large patches and ramps. However, pavement irregularities due to emergency and temporary works increased vertical accelerations in the aircraft that not only affected its structure and compromised the operational safety, but also compromised the safety of the military weapons on the aircraft.

Consequently, early studies on airport pavement roughness began to be published in the 50s. Authors such as Walls, Houboult & Press (1954), Potter (1957)

and Thompson (1958) performed the initial studies in order to establish quick and inexpensive methods for roughness data collection. These studies were conducted both in military and commercial airports characterized by large amounts of traffic. Results were presented as profiles of longitudinal runway height that provided an initial guide to establish a criterion for runway roughness and suitably for aircraft response calculations.

Over the years, other measurements were performed in order to increase the amount of data available for runway roughness studies. The old National Advisory Committee for Aeronautics (NACA) through the old Advisory Group for Aeronautical Research and Development (AGARD) acquired runway-profile data from 28 runways located in member countries of the North Atlantic Treaty Organization (Thompson, 1958). Years later, Turner (1963) presented runway roughness data from surveys of runways, taxiways and selected parking ramps of 17 Air Force bases in the United States in the form of profile and power spectral density plots.

Morris & Hall (1965a) comments that for several years the National Aeronautics and Space Administration (NASA), cooperatively with the airport operators, the old Federal Aviation Agency and the United States Air Force has conducted researches related to aircraft operating problems on rough runways and taxiing, take-off and landing loads. Nevertheless, other researches were also performed based on airplane maneuver difficulties resulting from rough runways that generally occurs during the high-speed portion of the take-off run and, occasionally, during the high-speed portion of the landing.

Other early studies on runway roughness measurement developed by NASA are described on the technical notes presented by Hall (1969; 1970; 1971; 1972a; 1972b) and Morris (1969). Such studies present three-track elevation profiles for several operational runways that were measured with conventional surveying methods (level, rod, and tape) and were given for use in studies of airplane response to and loads resulting from runway roughness.

As mentioned by Gerardi (1977b), the runway and the aircraft form a coupled system with the pavement profile providing a displacement input that can radically affect the behavior of the airplane. For this reason, there was an urgent need for a means to measure pavement roughness. The Federal Aviation Administration (FAA)

has long been aware of this need, and in 1973 initiated research and development efforts to quantify runway roughness. This effort began with the study of a means for rapidly collecting the runway profile. As a result of that effort, a profiling system using a laser beam as a horizontal reference datum was developed. In addition, Seeman & Nielsen (1977) completed a study of fifteen runway profiles to determine the relationship between roughness and B-727 response (cockpit vertical acceleration); to isolate segments of the runway that might be considered rough, and to outline a procedure to reduce overall roughness.

Nowadays, runway roughness is an essential issue for Airport Pavement Management Systems (APMS), both at the network and project level. Therefore, the recent efforts are being directed toward the development of new statistical approaches for runway roughness evaluation.

The first step to understand the pavement roughness concept is to know the definition of “Pavement Profile”. Sayers & Karamihas (1998) states that a profile is a two-dimensional slice of the pavement surface, taken along an imaginary line that shows the design grade, roughness, and texture (See Fig. 2).

Figure 2 Longitudinal pavement profile (Sayers & Karamihas, 1998)

A pavement profile can be measured along any continuous imaginary line on the surface and it is possible to measure the profile for a curved line as long as the line is a constant distance from the center line or some other reference that follows the own geometry.

Sayers & Karamihas (1996) states that a profile is a two-dimensional slice of the pavement surface, taken along an imaginary line. Profiles taken along a lateral

line show the superelevation and crown of the road or runway design, and also rutting and other pavement distresses. Longitudinal profiles show the design grade plus roughness.

Nevertheless, according to Hegmon (1992), no pavement surface is perfectly smooth, even though it may appear so to the naked eye. With sufficient magnification, roughness becomes evident on any surface. Pavement surface geometry of interest to airport engineers and managers covers a range from 0.01 mm to 120 m approximately in terms of bump length (wavelength), that is, a range of 12,000 to 1. This range is too wide to be measured on a single scale but can be described and measured in three scales: microtexture, macrotexture, and roughness.

It is easy to understand the pavement roughness concept. However, pavement roughness should not be confused with pavement micro-texture, macro-texture, and grooving because they are not sources of roughness. Pavement surface texture is categorized into mega (large scale irregularities that contribute to pavement roughness), macro, and micro texture, as shown in Figure 3.

Figure 3 Pavement surface texture categories (Haas, Hudson, & Falls, 2015)

As stated by OECD (1997 apud De Pont & Scott, 1999), pavement roughness has long been used as one of the primary indicators of pavement condition because of the direct impacts on users and the effects on ride quality and vehicle operating

costs. An OECD report made a distinction between the functional and structural conditions of the pavement and while road roughness is primarily a measure of functional condition it can also be an indicator of structural condition.

ASTM (2012) defines roughness as the deviations of a pavement profile from a true planar surface with characteristic dimensions that can affect vehicle dynamics, ride quality, dynamic loads, and drainage, and as mentioned by Sayers, Gillespie, & Queiroz (1984a, and b), induces vibrations in traversing vehicles.

According to Transport Canada (2016), airport pavement roughness is a lack of smoothness that exists when surface irregularities in the pavement profile are severe or extensive enough to interfere with the safe operation of aircraft or cause damage or structural fatigue in the airframe.

As stated by FAA (2009), airfield pavement roughness can be divided into two categories, based on the dimensions and frequency of surface deviations:

a) Single Event Bump (SEB): isolated events where changes in pavement elevation such as abrupt vertical lips or gradual deviations from a planned pavement profile occur at a distance of 100 m or less. Depending on the operational speed and bump length, SEB can affect aircraft suspensions since this systems are not able to totally absorb the energy produced when encounters it, making aircraft components and occupants feel the impact as a sudden jolt. SEB can be identified through conventional analysis (i.e. straightedge). However, to identify longer length bumps might be required a complete analysis of the pavement profile.

b) Profile Roughness (PR): surface profile deviations present over a portion of the runway that can increase fatigue on aircraft components, reduce braking action, impair cockpit operations, and/or cause discomfort to passengers. Depending upon size, weight, and operation speed, an aircraft may be excited into harmonic resonance due to profile roughness which can increase inertial forces or vibrations within the airplane structure.

Lee & Scheffel (1968), comments that the major cause of runway roughness is the aircraft moving over a pavement structure experiencing induced stresses and

deformations, and controllable and uncontrollable factors such as foundation soil structure, climate, aircraft weight, pavement composition, and traffic demand in the runway. In addition, other factors causing runway roughness are cited by Ksaibati et al. (1999):

1. Construction techniques that allow some variation from the design profile,
2. Repeated loads, particularly in channelized areas, that cause pavement distortion by plastic deformation in one or more of the pavement layers,
3. Frost heave and volume changes due to shrinkage and swell of the subgrade, and
4. Non-uniform initial compaction.

Furthermore, for Freeman et al. (2016), asphalt concrete pavement roughness can be a combination of three distress types: corrugation, depression, and swelling.

USACE (2009) defines corrugation (Fig. 4) as a series of closely spaced crests (perpendicular to the traffic direction) and waves occurring at fairly regular intervals, usually less than 1.5 meters along the pavement. The usual cause of this type of distress is the traffic action combined with an unstable pavement surface or base.

Figure 4 Corrugation (USACE, 2009)

Depressions (Fig. 5), on the other hand, are localized pavement surface areas having elevations slightly lower than those of the surrounding pavement that could cause hydroplaning of aircraft. According to Paveair (2018), light depressions are only noticeable until after a rain, when water accumulates in the basins formed.

Settlement of the foundation soil and wrong construction processes are the principal causes of this distress.

Figure 5 Depression (Paveair, 2018)

Shahin (2005) defines swelling (Fig. 6) as a protuberance in the pavement surface that may occur abruptly over either a small area or over a longer and gradual wave and that is usually accompanied by surface cracking. The principal causes of this distress are the frost action in the subgrade and the expansive soils (swelling soils). Moreover, small swelling can also occur on the surface of an asphalt overlay over Portland Cement Concrete overlays (PCC) as a result of a blow-up in the slab.

Figure 6 Swelling (Paveair, 2018)

As described by FAA (2016), swelling soils are clayey soils that exhibit a significant volume change caused by moisture variations. Airport pavements

constructed on swelling soils are subject to differential movements causing surface roughness and cracking.

In addition, according to Paveair (2018), roughness in concrete pavements could be caused by settlement or faulting (difference of elevation) at a joint or crack caused by upheaval or consolidation (see Figure 7).

Figure 7 Faulting in PCC (Paveair, 2018)

2.1.2 Airport vs. Highway Pavement Roughness

Although road roughness is an indicator of road condition and ride quality in terms of pavement performance and user costs, airfield pavement roughness is not defined by perceived passenger discomfort. Unlike highways, passenger discomfort due to runway surface irregularities is often not a significant issue since the degree of discomfort is small and the time of exposure is limited to a few seconds. Once passenger discomfort commonly occurs during takeoff and landing operations, there are other factors that can disturb passengers, such as the engine and aerodynamic noise, and the horizontal acceleration or deceleration.

Automotive suspension systems are designed to reduce the impact of common surface irregularities and improve overall ride quality. In contrast, aircraft suspension systems are designed to absorb the energy expended during landing. Due to the magnitude of the energy that must be addressed, aircraft suspension systems have less capacity to dampen the impact of surface irregularities. Thus, for the airport industry, pavement roughness is defined in terms of fatigue on aircraft components because of increased stress and wear, and in terms of cockpit

vibrations, excessive g-forces, and dynamic loads which are factors that may impair the safe operation of the aircraft (FAA, 2009).

As well as for crew and passengers, an aircraft reacts adversely when encountering pavement surface irregularities experiencing structural damage. In consequence, the excessive vertical accelerations developed in the aircraft can also result in dynamic loads to the pavement, accelerating the deterioration of load-related distresses. Therefore, rough runways can lead to increased aircraft stopping distances reducing the calculated effective runway length for both takeoff and landings.

2.1.3 Importance of Assessing Roughness

Airfield pavement roughness must be analyzed by airport managers and engineers since it is an essential factor that supports the decision-making process of the maintenance and rehabilitation (M&R) plans. Also, as stated by Lee & Scheffel (1968), runway roughness is a particularly important consideration as aircraft gross weights increase in terms of safety, initial construction costs, maintenance costs, and useful life of runways.

It should be noted that the effect of runway roughness on an aircraft depends on the aircraft type, weight, and operational speed. Thus, a runway may be a source of complaints by crews of a particular aircraft type, but be considered acceptable by crews of other types of aircraft.

According to Morris & Hall (1965b), there are three principal reasons that concern pilots about pavement roughness: apprehension of causing structural fatigue damage to the airplane, crew and passengers discomfort associated with the imposed accelerations, and degradation of the ability to precisely control the airplane during the take-off and landing maneuvers.

Difficulties such as fatigue damage, structural failures, and pilot response/feedback can be a consequence of the motions and loads caused by pavement roughness. Additionally, other factors that contribute to intensifying the problem are the use of high-pressure tires, increased taxiing speeds, increased

structural flexibility, and also the use of large external stores in military aircraft (Milwitzky, 1959).

Moreover, for Houbolt (1958, apud Plantema & Buhrman, 1963) the primary difficulties encountered as a consequence of runway roughness are:

- a) Structural failures of certain large aircraft carrying heavy masses on outboard regions of wings, such as engines, tanks, and missiles;
- b) Difficulties in reading panel instruments in the cockpit;
- c) Concern about the fatigue life of the aircraft structure and landing gears; and,
- d) Pilot complaints concerning taxiing behavior, such as fluctuation and a tendency to become prematurely airborne due to the oscillations of the aircraft.

Thus, the roughness data extracted from an airfield pavement profile can be useful for airport managers in order to monitor the condition of an airfield pavement network for APMS, assess the quality of newly constructed or repaired sections, identify critical locations and determine appropriate maintenance and rehabilitation (M&R) activities, and study the condition of specific sites of research (Sayers & Karamihas, 1998).

In line with Sonnenburg (1976), there is a need to develop the capability to state in a quantitative manner when and where a pavement is too rough. The effort is directed toward providing an airport operator with sufficient detailed information to execute adequate repairs at a minimum cost. However, it is important to keep in mind that the question of whether a runway is rough can be a subjective issue because it also depends on pilot interpretation, his experience, and the type of operation performed (Houbolt, Walls, & Smiley, 1955).

2.1.4 Equipment for Roughness Measurement

Through the years, pavement roughness has been quantified by profilometers, profilographs, vehicles equipped with accelerometers, or response-type systems. As stated by Sayers & Gillespie (1984) and Sayers, Gillespie, & Patterson (1986), the devices for roughness survey data collection in use all over the world can be

categorized into four generic classes based on how directly their measures pertain to the International Roughness Index – IRI (this index will be described later):

Class 1. Devices that produce precision profiles (true profiles). This class represents the highest standards of accuracy for roughness measurement. The principal devices considered in this class are Automated Rod and Level (AR&L), Face Dipstick, Walking Profiler G2, Digital Profilite 300, CS8800 walkable profiling system, TRL profilometer, and Australian Road Research Board Profiler (van Gelder & Stet, 2009).

Class 2. Devices that produce relative profile data (measures elevations in the pavement profile related to an external reference). In this class are included all other methods in which profile is measured as the basis for direct calculation of the IRI, but which are not capable of the accuracy required for a Class 1 measurement. Some devices that correspond to this class are High-speed roughness profilometer (ARAN), Non-contact lightweight profiler, Portable laser profiler systems, Multi-laser profiler vehicle, LaserProf (Laser/SPD), California profilograph, and French Longitudinal Profile Analyzer (van Gelder & Stet, 2009).

Class 3. Response Type Road Roughness Meters (RTRRMs). The measurements obtained from these systems are calibrated to the IRI scale by correlation with reference measures from a Class 1 or 2 devices. Some devices that fit into this class are the Brazilian Longitudinal Roughness Integrator IPR/USP, Maysmeter, MERLIN, Riley, and TRL Bump Integrator and are suitable for routine monitoring of a pavement network. However, their principal disadvantages are the need to maintain the vehicle's dynamic characteristics over time in order to get consistent results from year to year and the inability to compare results between these types of devices (De Pont & Scott, 1999).

Class 4. Subjective ratings and uncalibrated measures. Subjective evaluations are indicated when a roughness database is required and there is a need to relate the measures to the IRI scale, but high accuracy is not essential. In this class, a roughness measure is not reproducible or stable with

time, and can only be compared to IRI by subjective estimation. Additionally, an alternative is to use uncalibrated devices that can make measurements and convert them to the IRI scale.

According to Buttlar & Islam (2014) and Douangphachanh & Oneyima (2014), in spite of the variety of devices available for roughness evaluation, still exist difficulties to situate a device type into their corresponding class due to issues involving precision, accuracy, high productivity, and low cost.

Additionally, as stated by Bisconsini et al. (2018), several systems use profilometers and sophisticated tools, with high acquisition and operation costs, which often require the certain ability of the operators. In this context, profiler users face a critical problem related to lack of knowledge involving technology. To solve this problem, Sayers & Karamihas (1996) prepared a short course on profile measurement and analysis called “The Little Book of Profiling” in order to introduce new users to the basics of what profilers are, how they work, and what can be done with their data.

For airport pavements, the conventional devices used to evaluate runways are short. Commercial aircraft are large vehicles which operate at fast speeds and therefore respond to long bumps and dips, generally up to 100 m. However, smoothness specifications stated by FAA (2014a) call for a 3.6 m straightedge or a 7.6 m California Profilograph. The comparison shown in Figure 8 provides an idea of the wavelength that the profilograph can detect and the wavelength that is requested by a commercial aircraft. The figure shows the distance from nose to main wheels of a Boeing 777-200ER equal to 26 m and beneath the aircraft is a scale representation of a California Profilograph with 7.6 m in length.

Figure 8 B-777-200ER gear spacing and California profilograph length (APR, 2018)

Evidently, there is a need to use a device that can find both long and short wavelengths. Nowadays, there are several devices that measure runway pavement profiles accurately and allow seeing how an aircraft actually responds to the profile, through aircraft simulation and straightedge lengths that are similar to the gear spacing of the actual commercial aircraft.

Nevertheless, Gerardi (1997) states that many contractors and airport operators have adapted equipment designed for highway used to evaluate runway and taxiways for roughness. While these methods do provide some roughness information, they are not designed to consider all of the parameters that affect aircraft dynamic response. As shown in Figure 8, a Boeing 777-200ER has a gear spacing of 26 m and a takeoff speed of about 180 knots (333 km/h). It will respond to roughness a car or truck will never see and therefore a suitable device for airfield pavement roughness evaluation is necessary.

The Auto Rod and Level (AR&L) shown in Figure 9, for example, is a modern suitable device which can survey a line of 3,300 m in length in approximately 60 minutes collecting an elevation data point every 25 cm with elevation accuracy of 1 mm (APR, 2018). The AR&L device is based on the methodology of a traditional rod and level surveying but replacing the rod with a digital mast that records the elevation reference established by a rotating construction laser providing accurate data at a fast rate of speed.

Figure 9 Auto Rod and Level (AR&L) for measuring airfield pavements (APR, 2018)

Although other devices for roughness evaluation are available, the choice of the most adequate for airfield pavements depends on the purpose of the use of the data, as well as the time required for the survey and the availability of financial resources. For this reason, it is recommended that the equipment for airfield pavements roughness data collection be within Category 1 and have the following characteristics:

a) High speed in data collection in order to reduce operator exposure to the risks of air traffic, preferably with bright flashing LED lights which make the equipment more visible in the field;

b) Rolling inclinometer with damped suspension in the inertial stabilizer for ensuring stability and accuracy at all speeds and surface conditions;

(c) Capability to compute multiple roughness indexes such as the Boeing Bump Index, IRI, Ride Number, Profile Roughness Index and Profilograph Index; and,

(e) Programmable digital filters (preferably of the Butterworth type of third order), as well as moving average filters in order to remove shorter wavelengths.

However, as stated by Ferritto & Forrest (1976), some devices can require interruption of aircraft operations on the pavements to be surveyed. It is often not possible to close operational airfields long enough to obtain accurate surveys. Consequently, to determine the runway profile, automated techniques which minimize shut-down time are desirable and would have the following characteristics:

1. Make a large number of measurements in a short time;
2. Store data in an accessible manner either on local memory and on external devices of high capacity;
3. Be rugged and transportable; and,
4. Measure abrupt changes of the pavement surface as well as gradual changes over both large and small distances.

In addition, Gerardi (1997) argues that from an aircraft ride quality point of view, runway profile data must contain all wavelengths up to at least 150 m in length.

Ideally, a topographical survey of the runway profile is preferred because it will also include the overall grade changes in the runway. The grade changes on some runways can make a significant difference in the required takeoff distance. Therefore, the aircraft may encounter a rough area at a different speed, which will alter the way the aircraft responds to the roughness.

Aerodrome operators must monitor runway roughness through measurements collected with suitable equipment that allow obtaining values expressed according to a certain pavement roughness scale.

Survey results should be documented in a report containing not only pavement roughness indexes, but mainly the measurements of the elevation profile. Without this information, it is impossible to perform detailed roughness analysis for aircraft dynamic response. This has been a big problem since most of the regulations on pavement roughness in the world do not require specific reports for elevation profile information. Consequently, companies hired for this service delivery reports indicating only pavement roughness by sections through a single index (usually IRI).

Runway and taxiways profiles change with time usually as a result of settling, resurfacing, and new construction. For this reason, Potter (1957) suggests taking profile measurements along a line parallel to the left and right of the center line of the runway or taxiway, approximately along the paths of the main gear of an aircraft landing or taking off in the direction indicated by the runway designation. Thus, as stated by ANAC (2019), runway and taxiway roughness must be measured along their entire length, as defined in Table 1:

Table 1 Locations of runway and taxiway pavement roughness measurements (ANAC, 2019)

Aircraft wingspan (m)	Measurement Location respect to the runway centerline (m)	Minimum number of measurements
< 36	3	Once on each side
< 80	3 and 6	Once on each side for the two locations

Nevertheless, FAA (2009) suggests measure pavement runway profiles along the centerline and at the left and right offsets that approximates the aircraft using the airport. A 3 m offset is suitable for aircrafts wingspan up to 36 m (Airplane Design Group - ADG II and III aircraft), while a 5.2 m offset are appropriate for aircraft

wingspan above 36 m (ADG IV, V, and VI aircraft). The ADG list can be consulted in FAA (2014b).

Figure 10 (a) shows profile measurements at a typical airport, and (b) illustrates the three-track profiles, where the middle line is the runway or taxiway centerline. Multi-track profiles are necessary in order to compute aircraft response properly taking into account the effects of pitch and roll excitation at the landing gear (Hall et al. 1971).

Figure 10 (a) Profile measurements at a typical airport; (b) Three-track Profiles (Hall et al. 1971).

In addition, ANAC (2019) states that the frequency of the measurements depends on the average daily landings at the main runway threshold, as described in Table 2:

Table 2 Minimum frequency of airfield pavement roughness measurements (ANAC, 2019)

Average daily landings at the main runway threshold, in the last year	Measuring Frequency (every number of months)
Less than 15	36
16 to 30	24
31 to 90	24
91 to 150	18
151 to 210	12
More than 210	12

In general, airfield pavement roughness reports should be sent to the correspondent authority within a maximum period of thirty days after the completion of measurements.

2.1.5 The Role of Roughness on Airport Pavement Management Systems

According to NCHRP (2017), Pavement Management Systems are recognized as important tools to help transportation agencies optimize the use of available

funding, better communicate funding needs, and more objectively manage their pavement network. Management activities of an APMS are divided into two levels: network and project level.

Conforming to ACRP (2011), the principal stage into a network level APMS is to decide at a given time which pavement sections are prioritized to receive M&R treatments. Their objective is to identify and prioritize future pavement preservation needs, treatments, and projects. In other words, management activities carried out at the network level concern all of the airport pavements and, consequently, the decision-making process involves planning, budgeting, or/and policy decisions. On the other hand, project level activities concern specific pavement sections. At this level, the decisions are a consequence of the network level management. Decisions at project level result in the selection of project-specific pavement preservation treatments, including the selection of construction materials, procedures for implementation, and construction and subsequent monitoring of the treatment performance. This thesis is focused on the APMS at a network level.

As reported by Harrison & McNerney (1998), pavement roughness is an overlooked problem in APMS. Rough pavements can accelerate aircraft fatigue from both the dynamic response of the aircraft as well as accelerated loading on the pavement. In other words, rough runways and taxiways cause aircraft fatigue damage and therefore, is an aircraft safety issue because it can reduce pavement life, reduce aircraft stopping ability, and cause pilots and passenger complaints.

In consequence, pavement roughness evaluation is extremely important to the network level APMS process as it provides the pavement manager with a direct measurement influencing the public's perception of the quality of service provided by the pavement. In addition, APMS at network level offers advantages for airport executives and chief engineers because it can assist small, medium, and large airports in allocating their funds in a more optimal way to maintain their entire network in better condition.

As state by Haas, Hudson, & Falls (2015), a database is the central feature of an APMS. Roughness pavement data, together with structural, distress, and safety/skid data, is applicable to either rehabilitation or maintenance decisions.

Figure 11 shows the distribution of the types of data collected by state highway agencies in the USA for project and network level applications. Due to the existent analogy between road and airfield pavements, this distribution can also be valid for airfield pavements.

Figure 11 Types of pavement condition data collected for pavement management (NHCRP, 2009)

Pavement profile data has been used for construction quality control where precise measurement of roughness is needed to help define contractor pay factors. Profile data is usually used for pavement design/construction in order to estimate the minimum overlay thickness needed to achieve a desired level of smoothness after construction. In addition, aircraft simulation technology allows assessing airport pavements for ride quality. When used as a pavement management tool, the simulations will mark areas of the pavement that should be evaluated for roughness in more detail and perhaps repaired (Gerardi, 1997).

In agreement with Sayers, Gillespie, & Patterson (1986), the design of a project for surveying pavement roughness should start with a clear understanding of the objectives to be achieved from the measurement effort. Due to the substantial investment of manpower and money that can be consumed in a typical project, it is desirable to design the program carefully, taking in to account the project goals, the resources available, and the environment of the project.

As stated by FAA (2013), determination of roughness maintenance requirements in an APMS is critical because it will affect pavement serviceability and budget decisions.

2.1.6 Maintenance & Rehabilitation Treatments

Airport operators are responsible for the airside pavement maintenance in order to ensure the safety and efficiency of aircraft operations using the available budget. However, as stated by FHWA (2014), the selection of the appropriate treatment alternative implicates the recognition of the visible pavement distresses indicating potential roughness problems. Consequently, as suggested by Milwitzky (1959), regardless of the M&R to be used, airport operators should first identify the level at which roughness becomes a problem and then the way in which the pavement surface (runway or taxiway) can be repaired. In order to improve pavement smoothness on AC and PCC airfield pavements, (ACRP, 2011) suggest the following techniques for Corrective and Minor and Major Rehabilitation treatments:

Diamond grinding (AC and PCC pavements) – Corrective Maintenance treatment

This is a cost-effective rehabilitation technique that removes a shallow depth of pavement surface material by saw cutting closely spaced grooves into the pavement surface using diamond-tipped blades. Figure 12 illustrates a self-propelled diamond grinding machine. This technique can improve pavement smoothness through a diamond grinding that is applied only to selected areas of the pavement removing up to 2 cm from pavement surface. Diamond grinding can be an alternative in both asphalt and PCC pavements. However, this technique generally cannot remove roughness caused by long wavelengths, being most effective at removing roughness caused by faulted joints. Although grinding is frequently used to correct roughness problems, it also has a positive impact on a pavement's friction and noise characteristics.

Figure 12 Schematic of diamond grinding operation (ACRP, 2011)

Texturization using fine milling (AC pavements) – Corrective Maintenance treatment

Milling is done by a cylindrical milling drum with closely spaced carbide-tipped tools (teeth). This technique improves pavement smoothness and pavement friction and comprises conventional milling, precision milling, and fine milling which differs by the spacing of the cutting teeth and by the degree of control over the profile of the milled surface, as shown in Figure 13. Roughness problems are solved by milling of protruding pavement features such as bumps, faulting at transverse cracks, and rutting.

Figure 13 Schematic of milling operation (ACRP, 2011)

Machine patching (AC pavements) – Minor Rehabilitation treatment

This maintenance technique involves placing and spreading of hot or cold premixed bituminous materials using a mechanical paver on parts of a pavement section. Figure 13 shows this process that consists on the application of a tack coat, placement of the patching material, and compaction. Besides being suitable for pavement roughness due to subgrade settlements, machine patching is appropriate to repair localized areas of raveling and segregation, alligator cracking, potholing, rutting, and frost heaving.

Figure 14 Schematic of machine patching operation (ACRP, 2011)

Slab stabilization and slabjacking (PCC pavements) – Minor Rehabilitation treatment

This rehabilitation technique stabilizes pavement slabs by pressurized injection of grout underneath the slab, slowing down the erosion of base and subgrade materials caused by excessive pavement deflections (see Fig. 15). Slab stabilization fills voids underneath PCC slabs with grout but does not raise slabs, while slabjacking fills voids underneath PCC slabs and raises the grade of the slabs. Particularly, slabjacking is most suitable to improve pavement smoothness since it can raise PCC slabs by over 5 cm.

Figure 15 Construction sequence of slab stabilization procedure (ACRP, 2011)

Full-depth patching (PCC pavements) – Major Rehabilitation treatment

Full-depth repairs restore the smoothness and structural integrity of the pavement and to arrest further deterioration. The objective is to repair slabs damaged by subgrade settlement, frost heaving and other distresses such as deteriorated concrete (particularly near joints), corner breaks, mid-slab cracking, slabs with poor load transfer, and slabs where dowels are exposed. This rehabilitation technique involves full-depth removal of an entire or substantial part of a slab, installation of load transfer devices, and the replacement of PCC material. Figure 16 shows the sequence of the operation.

Figure 16 Sequence of operation of full-depth repair of PCC pavements (ACRP, 2011)

It is important to keep in mind that other rehabilitation techniques such as partial-depth repairs (PDR) may have differences in elevation between the repair areas and the existing pavement that results in increased roughness. For this reason, if PDR is necessary, is desirable to blend it into a concrete pavement with diamond grinding, in order to provide a smooth surface that matches the surrounding pavement.

Bonded PCC overlay (PCC pavements) – Major Rehabilitation treatment

Bonded PCC overlays are used to improve pavement smoothness and pavement surface friction and to increase the structural strength of the pavement. It consists in a thin PCC overlay (5 to 13 cm thick) placed directly on the surface of the existing PCC pavement with the overlay bonded to the existing pavement and is constructed as jointed plain concrete pavements with transverse and longitudinal joints matching those in the underlying pavement as shown in Figure 17.

Figure 17 Bonded PCC Overlay (ACRP, 2011)

Bonded overlays are suitable to increase the structural strength of the pavement. However, this is not an appropriate technique if load-associated pavement distresses are already visible since bonded overlays are unable to avoid the progression of faulting. Furthermore, scaling and durability cracking are distresses that limit the ability of the overlay to bond with its base.

In addition, Haas, Hudson, & Falls (2015) suggest the use of Combined Rehabilitation and Preventive/Preservation Treatment Alternatives at the Network Level. Tables 3, 4, and 5 show typical treatments used to improve asphalt pavement roughness. Unit costs are approximate and for the year 2018.

Table 3 Common preventive maintenance treatments for pavement roughness (AC pavements)

Treatment	Applicability	Approximate Unit Cost (\$ US)	Expected Service Life (Years)	Expected Effect	Usual IRI to repair (m/km)	Remarks
Thin Overlay (40 mm or less in thickness)	Rough pavements with or without surface deficiencies but structurally adequate; can be applied to structurally inadequate pavements to defer grade widening or reconstruction	\$7.00/m ² to \$9.00/m ²	≤ 10 years (structurally adequate pavement) ≤ 5 years (structurally adequate pavement)	Reduces IRI	≥ 1.9	May not be able to meet quality acceptance smoothness specifications
Hot-In-Place Recycling (HIR)	Rough but structurally adequate pavements; interim measure to improve ride quality until overlay needed	\$9.00/m ²	≤ 8 years (structurally adequate pavement) < 8 years (structurally adequate pavement)	Reduces IRI and improves surface condition	≥ 1.9	Pavements with severe deficiencies (e.g. rutting) may not be suitable candidates
Cold Mill and Inlay	Rough and/or rutting distress but structurally adequate pavements; interim measure to improve ride quality until overlay needed	\$11.00/m ²	≤ 10 years (structurally adequate pavement) < 10 years (structurally adequate pavement)	Reduces IRI and improves surface condition	≥ 1.9	Typically 50 mm cold mill depth

Table 4 Common structural preservation treatments for pavement roughness (AC pavements)

Treatment	Applicability	Approximate Unit Cost (\$ US)	Expected Service Life (Years)	Expected Effect	Usual IRI to repair (m/km)	Remarks
Reprofiling by Cold Milling and Overlay	Rough pavements with or without surface deficiencies and modest strengthening needs	\$11.00/m ²	≤ 15 years	Reduces IRI and improves general roughness; restores structural integrity	≥ 1.9	Overlay based on structural design
Structural Overlay	Structurally deficient pavements as determined by condition evaluation and/or deflection testing, or other means	\$12.00/m ² to \$20.00/m ²	10 or 20 years (according to design project)	Reduces IRI and improves general roughness, increases or restores structural integrity	> 3.0	Structural deficiency can result from under design or increased traffic loading

Table 5 Common reconstruction treatments for pavement roughness (AC pavements)

Treatment	Applicability	Approximate Unit Cost (\$ US)	Expected Service Life (Years)	Expected Effect	Usual IRI to repair (m/km)	Remarks
Cold In-Place Recycling	Excessive roughness and/or structural damage	\$45.00/m ²	≤ 15 years	Restores IRI, restores structural integrity	> 3.0	Need surface wearing course
Full Depth Reclamation and Stabilization	Excessive roughness and/or structural damage	\$45.00/m ²	≤ 15 years	Restores IRI, restores structural integrity	> 3.0	Need surface wearing course
Reconstruction	Excessive roughness and/or structural damage	\$45.00/m ²	≤ 15 years	Restores IRI, restores structural integrity	> 3.0	Need surface wearing course

Supplementary information about pavement roughness-related M&R techniques can be consulted in MDOT (2010); CALTRANS (2008); SHRP (1993); ARRA (2001); FHWA, (2000), and IPRF (2003).

2.1.7 Research and Development

Actually, there are no official criteria that alert an airport authority when existing pavements have become too rough. As a consequence, most pavement repairs are driven by pilot complaints. Unofficial criteria such as ICAO specifications and the Boeing Method provide useful guidance. However, they are only a guide to not exceed certain isolated bump height and length combinations. According to Gerardi (1997), the main limitation is that they not account for multiple bumps and the complex interactions between the runway and the aircraft.

Efforts for the implementation of new pavement roughness procedures are being performed by the Airport Technology Research Program (ATRP). The ATRP directly supports the FAA's Advisory Circular system by conducting several research projects. All projects aim to improve the operational safety of airports, ensure the adequacy of engineering specifications, and develop data to support new standards.

The NextGen Research Plan is a 10-year (2012 to 2022) research plan implemented by the ATRP with a US \$250 million investment in airport safety and capacity (FAA, 2012a). It investigates the technologies, methods, materials, and procedures that will be required to accommodate the traffic growth as a result of the

implementation of new technologies in the airport systems. In this context, US \$15 million is being invested in 4 studies related to pavement surface geometry: (1) ride quality criteria in simulator studies, (2) comparison of full-scale aircraft response with simulator response, (3) runway intersection grading criteria, and (4) automated groove inspection software.

Additionally, the Airport Pavement R&D Program is another 10-year research program with a US \$129 million investment in airport pavement technology. This program develops research on pavement design, construction, and evaluation, such as mix design, material selection, environmental factors, maintenance, sustainability, and life-cycle description. All the efforts in this program will allow to studying one of the major challenges: the feasibility to extend the design life of runway pavements from 20 years to 40 years.

As can be seen in Figure 18, the Airport Pavement R&D Program is divided into three major research projects: (1) airport pavement design, (2) airport pavement materials, and (3) airport pavement evaluation. The individual projects 2 and 3 of the third major project (US \$52 million investment) are directly related to the development of new roughness standards for in-service pavements (US \$11 million investment) and to the pavement surface, profile data collection, processing, and analysis (US \$3 million investment).

In general, the development of new roughness standards for in-service airfield pavements (individual project 2) will allow quantifying the concerns to the airport authorities and aircraft manufacturers in terms of survey data from pilots and current roughness indexes computations on given elevation profiles. Both roughness data for the new standard, as well as the currently available data, will be stored in an FAA database for further analysis on APMS and pavement design. In April 2013, the project 2 research team proposed a New Specification for Boeing Bump Index Computations Based on Bump Template Simulations. It is a draft of a new standard that is under development by the ASTM E17 committee on Vehicle-Pavement Systems (ASTM, 2013).

On the other hand, the measurements, processing, and analysis of the collected profiles (individual project 3) will be standardized to provide repeatability

and reproducibility for the evaluation of airfield pavement surface conditions. Collection and analysis of longitudinal profile data are essential to consider extending pavement life from 20 to 40 years. The profile data will allow evaluating in-service pavement conditions of different pavement types and ages. Furthermore, the individual project 3 involves correlations with different profiling devices, comparisons of data collection and processing between airfields and highways, and collection of runway profile data to monitor pavements with 20 years of in-service life. Results intend to be considering for the development of new standards and procedures.

According to FAA (2013), the consequences of not doing R&D in Pavement Evaluation are: increased downtime of runways for inspection, maintenance, and repairs, increased M&R costs, decreased efficiency of nationwide budget spending, and lack of support for Advisory Circulars. Conversely, there are a lot of benefits with R&D in Pavement Evaluation. These benefits are effective budget allocations, increased pilot and passenger satisfaction (rideability), decreased aircraft maintenance costs, decreased accident rate, more accurate data reflecting airfield pavement conditions, reduced runway downtime, and reduce indirect costs such as passenger delay time and airport operation costs.

2.2 INTERNATIONAL ROUGHNESS INDEX (IRI)

2.2.1 Background

According to Gillespie (1992), because of their simplicity and low cost, Response-Type Road Roughness Measurement Systems (RTRRMS) was acquired by the US highway departments of approximately half of the states by the late 1970s. However, it was difficult to develop and maintain a database of road roughness conditions without extensive effort at controlling or compensating for vehicle changes by frequent calibration exercises.

This problem was addressed by the National Cooperative Highway Research Program in 1978 in the Project "Calibration and Correlation of Response-Type Road Roughness Measuring Systems" (NCHRP, 1980), which began the work eventually leading to the development of the IRI. The main objective of that research program was to develop a time stable means for calibrating response-type systems. A mathematical transform of the measured longitudinal profile was proposed as a

calibration reference. The analysis method was further developed, simplified, and standardized under funding from The World Bank. The index obtained with the standardized method was called IRI, and guidelines were prepared for measuring it with a variety of equipment.

Airport Pavement 10-Year R&D Program (2012 - 2022)		
Estimated Total Program Cost \$129 Million		
Airport Pavement Design	\$ 35 M	
Airport Pavement Materials	\$ 42 M	
Airport Pavement Evaluation	\$ 52 M	
Research Projects Airport Pavement Evaluation R&D Team	Estimated Project Start/Completion Dates (FY)	Estimated Cost (US\$ M)
1. Improvements to FAA Airport Pavement Software Programs	2013 - 2022	14.5
2. Development of New Roughness Standards for In-Service Airport Pavements	2013 - 2022	11.0
3. Pavement Surface, Profile Data Collection, Processing, and Analysis	2013 - 2019	3.0
4. Nondestructive Pavement Testing (NDT)	2013 - 2022	23.5
Project 1: Improvements to FAA Airport Pavement Software Programs		
Database of materials and construction costs/Airport Improvement Program repository	2013 - 2021	4.0
Life Cycle Cost Analysis database and procedures, structure optimization	2013 - 2019	1.5
Integrate design and evaluation software as web-based application	2013 - 2020	4.0
Incorporate artificial intelligence into FAA applications	2014 - 2022	2.5
Incorporate GPS into existing FAA programs	2014 - 2021	1.5
Integrate FAA PAVEAIR with other ANGE262 software programs	2014 - 2018	1.0
Project 2: Development of New Roughness Standards for In-Service Airport Pavement		
Comparison/reviews of current roughness indexes and standards	2013 - 2021	2.0
Comparison of full-scale aircraft response with simulator response	2014 - 2020	3.5
Statistical analysis to setup a limit for pavement serviceability	2018 - 2022	1.0
Ride quality criteria in simulator studies (Airbus simulator/instrumented Boeing 747)	2014 - 2022	4.5
Project 3: Pavement Surface, Profile Data Collection, Processing, and Analysis		
Runway profile data collection and analysis	2013 - 2017	1.0
Automated groove inspection software	2014 - 2018	1.0
Runway intersection grading criteria	2015 - 2019	1.0
Project 4: Nondestructive Pavement Testing (NDT)		
Evaluation of NDT applications in NDT vehicle	2014 - 2022	3.5
Automated crack detection/PCI software	2014 - 2021	6.5
Evaluate NDT technologies: LIDAR, RDD, and x-ray CT	2015 - 2020	4.0
Estimation of remaining airport pavement life using NDT technologies	2013 - 2020	4.0
Develop new applications and procedures for current structural and materials evaluation	2013 - 2022	1.5
Application of nanotechnologies for NAPTF and in-service airport pavements	2014 - 2022	3.0
Characterizations of pavement texture/evaluation of friction measurement technologies	2013 - 2018	1.0

Figure 18 Airport Pavement 10-Year R&D Program (FAA, 2013)

Although RTRRMs were used in many countries, to achieve consistent measurement performance rigorous calibration methods were needed that could be based on technology available at these sites. Equally important was the need for a standard scale of roughness that would be stable over time and transportable throughout the world to allow comparison of measurements on a worldwide basis. To address this problem the International Road Roughness Experiment (IRRE) was

organized and conducted in Brazil in 1982 (Sayers & Gillespie, 1984). The IRRE was held in Brasilia and was funded by a number of agencies, including the Brazilian Transportation Planning Company (GEIPOT), the Brazilian Road Research Institute (IPR/DNER), the World Bank (IBRD), the French Bridge and Pavement Laboratory (LCPC), and the British Transport and Road Research Laboratory (TRRL).

Since the publication of guidelines for obtaining IRI in 1986, it has become the most widely-used reproducible indicator of road roughness. The IRI is required for all data submitted to the FHWA Highway Pavement Management System database and is stored in the Long-Term Pavement Performance database (LTPP). Virtually all road profiling systems used in the world are equipped with software for computing IRI, and a variety of ASTM standards (ASTM, 2017a,b, and c; ASTM, 2018a, and b) exists for computing this index. Currently, the IRI has shown reproducible results over a variety of road measuring devices.

2.2.2 The Quarter-Car Model

As stated by Sayers & Karamihas (1996), the IRI is a profile-based roughness statistic that has become a standard scale on which road roughness information is reported in many countries of the world.

According to Gillespie (1992), the IRI is a scale for pavement roughness based on the response of a generic automobile to the roughness of the road surface. To determine an IRI value is essential to obtain an accurate measurement of the pavement profile that processes it through an algorithm that simulates the way a reference vehicle would respond to the roughness and accumulates the suspension travel. The IRI is calculated by accumulating the absolute values of the suspension deflection and dividing by the distance traveled. The units of IRI are generally expressed in m/km.

The IRI is a mathematical representation of the accumulated suspension stroke of an automobile, divided by the distance traveled by it. This index is calculated mathematically from the measured longitudinal profile with use a simple dynamic model is known as the “Golden Quarter-Car model (GQC)” along with a single wheel path (See Fig. 19).

Figure 19 The quarter-car model (Gillespie, 1992)

As shown in Figure 19, the model includes the major dynamic effects that define how roughness causes vibration in an automobile. Thus, the GQC model includes one tire represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and a damper, and the mass of the body supported by the suspension for that tire. This model uses a simulation speed of 80 km/h, where the simulated suspension motion is linearly accumulated and divided by the length of the profile to compute the IRI, as shown in Equation 1.

$$IRI = \frac{1}{L} \int_0^T |Z| dt \quad (1)$$

As indicated in Equation 1, the IRI can be defined mathematically as the integral of the absolute difference in suspension vertical velocity between the axle and the sprung mass of the GQC model relating to the pavement section length. The variable Z characterizes the suspension velocity due to the road excitations, which is the velocity difference between the unsprung mass Z_t (the portion of automobile body mass supported by one wheel) and the sprung mass Z_s (mass of wheel, tire, and half of axle/suspension). The integral of $|Z|$ represents the total rectified suspension travel for the time, T , required for the vehicle to travel a distance, L , along the road. The variable T is calculated from the length of the profile, L , and the simulated speed of 80 km/h.

According to Zamora Alvarez (2015), in calculating the IRI, the elevation profile data is first passed through a 250 mm “Moving Average Filter” before the GQC model is simulated. This filter simulates the physical tire behavior and their ability to reduce particular excitations from the pavement surface such as slight surface

irregularities and cracks. Once the pavement profile is measured and the filter is applied, the model is used to calculate the suspension velocity response for the pavement profile. As shown in Figure 19, when the suspension velocity response is integrated, the IRI accounts for the accumulated displacement difference (Z) of the vehicle sprung mass (Z_s), and the unsprung mass (Z_t), in response to the road excitation inputs (Z_R).

The coefficients used in the mathematical equations were those that provided the maximum correlation to the output of response-type roughness measuring systems. Table 6 presents the parameters used to compute the IRI based on the GQC model. The parameters are suitable for a typical passenger car and are normalized by the vehicle sprung mass (M) with the intention of simplifying the equations of motion and normalize the model for applicability into a larger range of passenger vehicles.

Table 6 Golden Quarter Car parameters normalized by the sprung mass, M	
Parameter	Value (M = sprung mass)
Suspension spring rate K_s	$K_s/M = 63.3 [1/s^2]$
Suspension Damping rate C_s	$C_s/M = 6.0 [1/s]$
Unsprung mass, m	$m/M = 0.15$
Tire spring rate K_t	$K_t/M = 653 [1/s^2]$
Constant vehicle speed = 80 km/h	

Still, Figure 19 shows that the frequency response of the quarter car ranges from 0.5 to 20 Hz with some emphasis on roughness at the body bounce frequency and at the axle resonance frequency. At 80 km/h these frequencies correspond to pavement profile wavelengths between about 1.1 and 44 m. However, as there is still some response to wavelength components outside this range, different authors vary a little in the wavelength range quoted. For Perera, Byrum, & Kohn (1998), the IRI is sensitive to wavelengths between 1 and 30 m, while Barella (2008) argues that this index is sensitive to wavelengths up to 50 m.

Thus, at very low frequencies (corresponding to long wavelengths in the road) the suspension response is zero because the wheel and the vehicle body move up and down together. Road inputs at frequencies near one Hertz cause the sprung mass to resonate on the suspension producing stroke that is slightly greater than the

road input. The response is maintained up through frequencies near 10 Hertz where axle resonance occurs. Above the axle resonant frequency, the response again drops to zero as the road bumps simply deflect the tire without producing significant suspension stroke.

De Pont & Scott (1999) states that because the IRI model includes the response to these longer wavelengths, it is usual to calculate IRI over road pavement sections of at least 200 m in length to obtain a reasonable sample of these components. Using sections of this length gives reasonably consistent results for repeat measurements of the same profile. Nevertheless, to obtain a reasonable sample on airfield pavements, sections can have at least 100 m in length. Further information about GQC model is given in Annex A.

2.2.3 Scope and Limitations

According to Sayers, Gillespie, & Patterson (1986) and Sayers, Gillespie, & Queiroz (1986), the IRI has been reported to be relevant as an indicator of pavement serviceability, independent of the particular equipment used to measure it, internationally and geographically transferable, and time stable. Furthermore, Hajek, Kazmierowski & Musgrove (1998) states that the IRI has become a well-recognized standard for measurement of road roughness and, consequently, has many advantages for highway agencies, as described below:

- a) General applicability of results: The results of studies undertaken by one jurisdiction and reported in standard IRI units should be directly transferable and usable by other agencies. This applies to the studies in the areas such as pavement roughness comparisons and pavement performance modeling;
- b) Equitable allocation of resources: Adoption of IRI by large highway agencies should encourage local transportation agencies to use IRI as well. A general use of IRI should lead to more equitable allocation of pavement preservation funds because pavement serviceability could be directly compared across the jurisdictional boundaries.
- c) Cost-effectiveness: There are quite a few companies that can measure IRI. Highway agencies can contract-out roughness measurements through a competitive bidding process. Conversely, companies providing pavement

roughness measurements need not own and operate a variety of different roughness measuring equipment and software in order to satisfy different customer requirements.

- d) Availability of pavement profiles: The use of the IRI calls for the measurement of actual pavement profiles. Knowledge of the pavement profile can also be used to determine the source of pavement roughness and to design appropriate maintenance and rehabilitation treatments on site-specific locations.

However, although the IRI is used worldwide, there are some limitations that need to be addressed. The two principal limitations are that the IRI can give similar roughness values for various pavement sections that vary significantly in elevation, and that the IRI is limited to automobiles. Furthermore, authors such as Delanne & Pereira (2001); Rouillard (2004); Loizos & Plati, 2008; Múčka 2016; and Múčka & Granlund, 2012a, and b) reported the following limitations of the IRI:

- The suspension stroke response does not cover all aspects of vehicle vibration such as ride comfort or road holding,
- In most cases, the frequency response of the GQC model for IRI calculation has a weak sensitivity to the wavelength contents below 2 m and above 20 m,
- IRI has a limited ability to detect road quality on a highway after repairs were made, probably because the IRI research was based on roads, which were often of low quality and low speed,
- IRI was developed when the maximum speed limit of 90 km/h was in effect in the United States,
- IRI does not consider the non-stationary nature of real roads,
- IRI cannot represent the dynamic behavior of the real vehicles.

In addition, FAA (2013) states that the IRI is not appropriate for airfields pavements since the aircraft pavement characteristics, loading conditions, dynamic movements responding to the pavement surface, and human factors are very different from highway traffic conditions.

Evidently, even though the popular use of the IRI as a roughness statistic, there exist many areas of improvement to obtain refined measures of roughness.

2.2.4 Current Ratings

The IRI, which has been established by the World Bank for highway use, is also used to quantify airfield pavement roughness as a general condition indicator. As illustrated in Figure 20, an IRI of 0 m/km means that the profile is perfectly smooth or flat, while IRI values above 8 m/km commonly correspond to damaged pavements that can be impassable except at reduced speeds. Although there is no theoretical upper limit to roughness, IRI values above 8 m/km are typically found on rough unpaved roads.

However, according to Stet (2006), the IRI is not suitable for airfield pavement roughness evaluation. The author argues that the IRI is not capable to assess long wavelength roughness or aircraft response. Aircraft predominantly respond to roughness events in pitch rotation. The response of the main landing gear will drive the response of the nose landing gear. Consequently, a single suspension response prediction like IRI will not detect longer wavelengths and their effect on aircraft ride quality.

Figure 20 IRI scale represented by different classes of pavement (Sayers & Karamihas, 1998)

Although IRI was not developed for airfield pavements, the literature, as shown in Figure 20, suggests that IRI values up to 2 m/km are suitable for airport runways and superhighways. In Brazil, for example, the National Civil Aviation Agency (ANAC) has established an IRI value equal to 2.5 m/km as a limit for airfield pavement roughness (ANAC, 2019).

Additionally, Transport Canada (2016) uses the historical subjective method of assessing runway pavement roughness called Riding Comfort Index (RCI). The RCI is based on IRI and rating roughness on a scale of 0 (very poor ride quality) to 10 (very good ride quality). This index gives a general indication of the average level of roughness experienced by the crew. Pilot complaints can be expected when the RCI falls below 5 or 4. Transport Canada established the correlation between the RCI and IRI as indicated in Equation 2, where “e” is the base of the natural logarithm (2.71828) and the IRI is expressed in m/km:

$$RCI = 10 * e^{(-0.255*IRI)} \quad (2)$$

Thus, if pilot complaints are expected when the RCI is below 5 or 4, then the equivalent in IRI is above 1.6 or 1.2 m/km.

Maintenance intervention thresholds in terms of IRI vary according to the country and road type. Analogous to Brazil and Canada, many countries use them to assess airfield pavement roughness. Table 7 shows the limit values of IRI adopted in some countries around the world.

2.3 BOEING BUMP INDEX (BBI)

2.3.1 Background

The Boeing Company through their Airport Technology Group has long been involved in the evaluation of runway roughness due to many requests from customer airlines and airport authorities. In 1968, Ethiopian Airlines request to comment about the condition of the runway at Addis Ababa, which was a rough runway from the point of view of many experienced pilots. Pilot complaints indicated that certain single bumps on the runway felt extremely hard during takeoff and landing, making the aircraft come into resonance with sharp jolts that seemed more severe than a hard landing. Boeing Company researchers determined that the severity of the jolt varied

depending on the operational speed and the bump length. This finding was the major motivation for the development of objective criteria based on single bump height and spacing limits (Boeing, 2002).

Table 7 IRI specifications around the world, adapted from Múčka (2017) and Souza et al. (2006)

Country	IRI rating (m/km)					Source
	Very Good	Good	Fair	Poor	Very Poor	
Austria	-	< 1.8	1.8 - 4.5	> 4.5	-	ARRTRA (2006)
Bosnia and Herzegovina AADT < 2000	< 2.6	2.6 - 3.5	3.5 - 4.3	4.3 - 4.9	> 4.9	RDF (2005)
Bosnia and Herzegovina AADT > 2000	< 1.2	1.3 - 1.5	1.5 - 2.2	2.2 - 3.1	> 3.1	RDF (2005)
Brazil	< 1.9	1.9 - 2.7	2.7 - 3.5	3.5 - 4.6	> 4.6	DNIT (2006)
Brazil	-	< 3.0	3.0 - 4.0	4.0 - 5.5	> 5.0	DNIT (2011)
Canada (Alberta) Highways - 110 km/h	-	< 1.5	1.5 - 1.9	> 1.9	-	ALBERTA (2018)
Canada (Alberta) Other Highways	-	< 1.5	1.5 - 2.1	> 2.1	-	ALBERTA (2018)
Chile	-	< 3.0	3.0 - 4.0	> 4.0	-	IMT (1998)
Costa Rica	< 1.0	1.0 - 1.9	1.9 - 3.6	3.6 - 6.4	> 6.4	UCR (2008)
Czech Republic	< 1.9	2.0 - 3.0	3.1 - 4.2	4.3 - 6.3	> 6.3	COSMT (2015)
Estonia	< 1.39	1.4 - 2.6	2.7 - 4.1	4.2 - 5.5	> 5.6	TCER (2001)
Holland	< 0.6	0.7 - 2.0	2.1 - 3.4	3.5 - 4.9	> 5.0	Sweere, VanZwieten, & Eijbersen (1996)
Honduras	-	< 3.5	3.5 - 6.0	> 6.0	-	IMT (1998)
Hungary	< 1.5	1.5 - 2.5	2.5 - 4.0	4.0 - 6.0	> 6.0	Gáspár (2012)
Ireland AADT < 2000	< 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 7.0	> 7.0	Feighan et al. (2015)
Ireland AADT > 2000	< 2.7	2.7 - 3.2	3.2 - 4.0	4.0 - 5.0	> 5.0	Feighan et al. (2015)
Ireland AADT Engineered pavements	< 2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 3.5	> 3.5	Feighan et al. (2015)
Ireland AADT Highways	< 1.5	1.5 - 2.0	2.0 - 2.5	2.5 - 3.0	> 3.0	Feighan et al. (2015)
Kazakhstan First class roads	< 2.0	2.0 - 2.3	2.3 - 2.4	> 2.4	-	MITRK (2003)
Kazakhstan Fourth to sixth class roads (cold AC and crushed stone)	< 3.8	3.8 - 4.2	4.2 - 4.6	> 4.6	-	MITRK (2003)
Kazakhstan Second and third class roads	< 2.5	2.5 - 2.8	2.8 - 3.0	> 3.0	-	MITRK (2003)
Kazakhstan Third class roads (cold AC and crushed stone)	< 3.5	3.5 - 3.8	3.8 - 4.2	> 4.2	-	MITRK (2003)
Kazakhstan Third class roads (gravel road)	< 5.4	5.4 - 5.9	5.9 - 6.4	> 6.4	-	MITRK (2003)
Mexico (private roads)	-	< 1.8	1.8 - 2.5	> 2.5	-	SCT (2016)
Mexico (public roads)	-	< 2.5	2.2 - 3.5	> 3.5	-	SCT (2016)
Poland AC First class roads	< 3.0	3.1 - 5.0	5.1 - 6.6	> 6.6	-	GDDP (2002)
Poland AC Highways and express ways	< 2.0	2.0 - 4.3	4.4 - 5.7	> 5.7	-	GDDP (2002)
Russia Fourth to sixth class roads (cold AC and crushed stone)	< 3.5	3.5 - 4.1	4.1 - 4.6	> 4.6	-	Mogilny, Lushnikov, & Krasikov (2013)
Russia Highways and first class roads	< 1.2	1.2 - 1.7	1.7 - 2.1	> 2.1	-	Mogilny, Lushnikov, & Krasikov (2013)
Russia Second and third class roads	< 1.7	1.7 - 2.2	2.2 - 2.6	> 2.6	-	Mogilny, Lushnikov, & Krasikov (2013)
Russia Third class roads (cold AC and crushed stone)	< 3.2	3.2 - 3.7	3.7 - 4.1	> 4.1	-	Mogilny, Lushnikov, & Krasikov (2013)
Russia Third class roads (gravel road)	< 4.9	4.9 - 5.6	5.6 - 6.4	> 6.4	-	Mogilny, Lushnikov, & Krasikov (2013)
Slovakia First and second class of roads	< 1.9	1.9 - 3.3	3.3 - 5.0	5.0 - 10.0	> 10.0	MDVRR (2012)
Slovakia Freeways	< 1.9	1.9 - 3.3	3.3 - 5.0	5.0 - 8.0	> 8.0	MDVRR (2012)
Slovakia Third class and local roads	< 3.3	3.3 - 5.0	5.0 - 8.0	8.0 - 14.0	> 14.0	MDVRR (2012)
Slovenia AADT < 2000	< 2.6	2.6 - 3.5	3.5 - 4.3	4.3 - 4.9	> 4.9	MZP (2003)
Slovenia AADT > 2000	< 1.2	1.3 - 1.5	1.5 - 2.2	2.2 - 3.1	> 3.1	MZP (2003)
Spain	< 1.5	1.5 - 2.5	2.5 - 4.0	> 4.0	-	Rio (1997)
Uruguay (AC)	< 3.2	3.2 - 3.9	4.0 - 4.6	> 4.6	-	IMT (1998)
Uruguay (PCC)	< 2.8	2.8 - 3.5	3.6 - 4.3	> 4.3	-	IMT (1998)
USA	-	< 1.8	1.8 - 3.2	> 3.2	-	FHWA (2017); Shepherd (2017)
USA Federal-aid urbanized areas	< 1.5	1.5 - 1.9	1.9 - 2.7	2.7 - 3.5	> 3.5	HPMS (2016)
USA Rural roads	< 1.0	1.0 - 1.5	1.5 - 1.9	> 2.3	-	HPMS (2016)
USA Urban roads	< 2.7	2.7 - 3.1	3.1 - 3.5	> 3.5	-	HPMS (2016)

In early studies, subjective criteria were developed to provide a general indication of the amount of allowable roughness in order to minimize passenger and crew discomfort. However, the difficulty in establishing an acceptable level of fatigue and human acceleration made that the criteria were based on data previously obtained from taxi experience. This data was the result of the research developed by Richmond et al. (1968) which analyzed the taxi response of large military aircraft on paved and semi-prepared surfaces. As a consequence, a preliminary single event bump criterion in terms of bump height and bump length was established.

After several years of research, The Boeing Company finally developed a simple method to easily detect and repair pavement roughness. The method called “The Boeing Method” was documented by Boeing (2002) and has been supported by many major manufacturers that have accompanied the development of the method and use it since the late 1970s.

The Boeing Method takes into account the direct effect on aircraft structure through a discrete surface deviation evaluation of the pavement surface measured by a close interval elevation survey. The survey results are plotted and the discrete bumps are compared to the Boeing criteria developed for commercial aircraft.

As stated by Gervais (1991), The Boeing Method can be used to repair or to alert M&R needs at specific runway sections, and to provide temporary ramp dimensions for use in nighttime or off-peak-hour paving with asphaltic materials. Temporary ramps are necessary in pavement repair or rehabilitation, specifically at the end of each work period in order to allow daily aircraft movements. The design of the ramps should minimize wasted paving materials and provide a smoothness surface for aircraft that operates on a runway surface that is partially rehabilitated.

It is important to emphasize that the current runway roughness criterion specified by the International Civil Aviation Organization in Annex 14 (ICAO, 2016) correspond to the old Boeing Method that was published in 1989 and used from 1975 until mid-1994. According to Stet (2006), the Annex 14 contains only very general information regarding airfield pavement roughness.

Nowadays, The Boeing Company suggests the last criterion version that is available since 1995. FAA (2009) considers the 1995 criterion to assess pavement surface profiles in order to identify potential isolated bumps that can affect aircraft operations. It is suitable for runway applications and for heavily loaded aircrafts approaching takeoff speeds between 130 to 200 knots (241 to 370 km/h). However, conservative results are provided for taxiways and aprons since aircraft moving at taxi speeds or operating at a relatively lightweight usually experience moderate g-loads in comparison with the generated in a takeoff condition.

2.3.2 Procedure – The Boeing Bump Method

To analyze bump heights and lengths based on The Boeing Method it is necessary to understand the straightedge concept. A straightedge is a virtual or imaginary line that should be constructed between two points on the elevation profile in order to measure the deviation from the straightedge to the pavement surface, as shown in Figure 21. As can be seen, the bump height is the maximum vertical distance (positive or negative) from the straightedge to the pavement surface. On the other hand, the bump length is the smallest distance from either end of the straightedge to the location where the bump is measured.

Figure 21 Schematic of the bump height measurement (FAA, 2009)

There are maximum and minimum straightedge lengths. The Boeing Method considers straightedge lengths up to 120 meters. According to the Boeing Company, higher bump lengths do not contribute to dynamic aircraft response. In contrast, the minimum bump length is 50 cm that is equal to twice the survey interval of the pavement profile (25 cm). Figure 22 shows the minimum three points in the pavement profile that are necessary to obtain a deviation from the straightedge. Note that the two endpoints define the straightedge length, and the interior point provides a profile deviation.

Figure 22 Minimum straightedge determination (FAA, 2009)

As illustrated in Figure 22, several straightedges are located at any profile survey point (at the beginning, increments, and end of the straightedge). For each possible straightedge configuration, the method computes the bump height and bump length. Nevertheless, because of a large number of bump height and bump length combinations, computer software is essential for the performance of isolated bump analyses.

It is extremely important to emphasize that The Boeing Method is a simplified procedure based upon operational experience for single bumps describing the general condition of a runway pavement. The method was not addressed to attend the effects of a series of long wavelengths where aircraft response is important. However, all types of jet aircraft can apply this method regardless of their structural design or physical characteristics.

The current method developed by The Boeing Company is divided into three regions: acceptable, excessive and unacceptable, as shown in Figure 23. The purpose of the regions is to assist in interpreting the effect that single bumps have on aircraft response and in determining the need for corrective action. To do this, the method plots bump height and bump length against the acceptance criterion. The criterion was defined by Boeing (2002) and adopted by FAA (2009).

Figure 23 Current roughness acceptance criteria for single event bumps (FAA, 2009)

The Boeing Company and the FAA describe the regions on Figure 23 as follows:

a) Acceptable Region

Newly constructed or rehabilitated pavements are expected in this region. FAA (2014a) items P-401 (AC pavements) and P-501 (PCC pavements) specify construction tolerances of 0.6 cm in 3.7 and 4.9 m, respectively, while the ICAO standard is 3 mm over 3 m.

Aircraft operations in this region are acceptable for all aircraft whenever bump height and length combinations not adversely affect them. However, factors such as frost heave or isolated pavement distresses may lead to bump combinations that reach or also exceed the acceptable region. Vertical lips or faults, for example, are pavement surface distresses characterized by vertical deviation with zero length and, therefore, rarely cause problems in service because their size is usually within the acceptable range.

Pilot complaints about excessive roughness begin to be reported when the irregularities are closer to the excessive region. Airport complaints within

the acceptable region should be considered by airport operators, in order to identify bump locations or critical sections and to prepare them for monitoring the pavement profile and/or execute corrective actions.

In line with FAA, it is important to keep in mind that whenever roughness is above the acceptable region, aircraft gear fatigue becomes more critical than passenger discomfort or cockpit acceleration restrictions.

b) Excessive Region

Pavement roughness in this region should be corrected within a reasonable period in order to restore the surface condition to the acceptable limit region. In this region, aircraft response to excessive roughness begins to be noticed by pilots because of severe interference in the cockpit. Furthermore, roughness in the excessive region may also result in a short-term inability to steer the aircraft as well as an excessive reduction in the nose and main gear fatigue life. However, pavement repairs in this region do not require closing the pavement section.

c) Unacceptable Region

All bump height and length combinations within this region must result in the immediate closure of the runway, since structural damage may occur at any time. Pavement repairs should be addressed to restore the surface condition to an acceptable level.

The FAA provides the following mathematical models of the two criteria curves in order to assist in the development of software to compute the BBI. Table 8 summarizes the runway roughness criteria in numeric format.

1) Lower curve, which establishes the upper limit of the acceptable region.

For bump length, L , less than 20 m:

$$\text{Bump height} = 1.713187 + 0.800872 (L) - 0.031265 L^2 + 0.000549 L^3 \quad (3)$$

For L between 20 and 60 m:

$$\text{Bump height} = 6.4 + 0.16 \quad (4)$$

2) Upper curve, which establishes the upper limit of the excessive region

For L, less than 5 m:

$$\text{Bump height} = 2.747222 + 1.433399 (L) - 0.183730 L^2 + 0.013426 L^3 \quad (5)$$

For L between 5 and 20 m:

$$\text{Bump height} = 2.7590 + 1.085822 (L) - 0.053024 L^2 + 0.001077 L^3 \quad (6)$$

For L between 20 and 60 m:

$$\text{Bump height} = 7.775 + 0.20375 (L) \quad (7)$$

Table 8 Summary of the current runway roughness criteria for single bumps									
Bump Height limit by region (cm)	Bump Length (m)								
	3	6	9	12	15	20	30	45	60
Acceptable	3.9	5.5	6.8	7.8	8.5	9.6	11.2	13.6	16.0
Excessive	5.8	7.6	9.0	10.0	10.8	11.9	13.9	16.9	20.0

2.3.3 Filtering Considerations for BBI computation

Inertial profilers used in the highway industry includes highpass filters that modify the accelerometer signal before integration in order to avoid offset errors related to traveling on ramps, and braking and accelerating the test vehicle. The use of inertial profilers with highpass filters not only affects the computation of the BBI, but also the simulation of the aircraft accelerations. The reason is that the BBI and the simulation of the vertical accelerations take into account longer bumps in the pavement profile than in the computation of the IRI. Significant errors can be generated by highway profilers if the pavement profile is measured when the test vehicle is braking, accelerating, and cornering. Therefore, the FAA does not recommend computing BBI indexes or simulating aircraft accelerations if the airfield pavement profile is measure through highway inertial profilers including highpass filtering (FAA, 2009).

2.3.4 BBI Computation

Application of the Boeing Method requires that all possible straightedge lengths in the elevation profile be evaluated. This process is tedious and usually demands a lot of time. Moreover, it should be noted that for the selection of M&R activities to reduce roughness, the bump height and bump length are significant.

The FAA summarized the Boeing Method and created the Boeing Bump Index, an additional parameter that allows comparing the computed bump criterion with other measures of roughness such as the IRI. This index can be calculated through the five-step process described below.

- I. Firstly, the bump height and bump length shall be calculated for all possible straightedge lengths on a selected sample point in the elevation profile,
- II. Secondly, the calculated bump length is used in Figure 23 to determine their acceptable bump height. The acceptable bump height is the upper limit of the acceptable region,
- III. Thirdly, the measured bump height must be divided by the acceptable bump height,
- IV. Fourthly, the steps I through IV must be repeated for all sample point in the elevation profile,
- V. Finally, the BBI for the selected sample point is the largest of all values calculated in step III for the selected sample point.

Thus, according to Figure 24, a BBI value falls in the acceptable region if it is less than 1.0. BBI values greater than 1.0 can be fall in the excessive or unacceptable region.

Figure 24 Boeing Bump Index classification (FAA, 2009)

Evidently, the BBI is analogous to the Boeing Method and is based on the same three regions of roughness. Thus, the descriptions of these three regions discussed previously are valid for the BBI classification. Figure 24 recreates the three regions showed in Figure 23 in terms of BBI versus bump length.

2.3.5 Considerations about Ramps

As mentioned before, construction of temporary ramps of Hot-Mix asphalt is necessary for pavement repair or rehabilitation in order to provide a smoothness surface minimizing wasted paving materials. Furthermore, the ramps are required because pavement projects usually involve several phases to complete and often produce a non-uniform surface denying the transition of aircraft from elevation to elevation. FAA (2006) provides guidance on the construction of temporary ramps using Hot-Mix asphalt and suggests a 4.6 m ramp for each 2.5 cm of elevation change, as observed in Figure 23 by the black dashed line. This dashed line shows how the guidance on temporary ramps compares against the upper limit of the acceptable region. Note that elevation changes greater than 8 cm exceeds this limit and therefore the ramp length shall be adjusted.

FAA (2006) argues that the construction of temporary ramps is an important task in work periods because steep or irregular ramps could cause structural damage to the aircraft or difficult to read the cockpit instrumentation. On the other hand, in addition to the waste in materials and labor, longer ramps may result in potential damage to aircraft engines due to the ingestion of loosening temporary pavement materials.

Additionally, Boeing (2002) suggests two ways for construction of temporary ramps depending on the type of equipment available:

- 1) Temporary ramps constructed down to the original surface. These ramps provide good pavement joints and are suitable for the long-term support of aircraft loads. As illustrated in Figure 25, the ramp should be feathered to no less than the maximum aggregate size and should be sealed in order to prevent blast erosion. Cold-planing machines are appropriate to heel cut the pavement.

Figure 25 Heel-cut ramping technique (adapted from Boeing, 2002)

- 2) Heel-cut when paving operation is resumed. Short pavement heel-cut in previous ramps provides an adequate joint for aircraft support, as shown in Figure 26. When paving the final surface course, the transition ramp should be completely cut back and the entire transition removed.

Figure 26 Surface preparation prior to resumption of paving (adapted from Boeing, 2002)

2.4 AIRCRAFT DYNAMIC RESPONSE

2.4.1 Aircraft Landing Gear Systems

As stated by FAA (2012b), landing gears are the primary structural members of the aircraft and are designed to support their entire weight during landing and ground operations. The landing gear configuration depends on the aircraft design and its intended use. It has a direct impact on the capability of pavement to support an aircraft.

Commercial aircraft generally have a tricycle-type landing gear arrangement comprised by a nose and main landing gears. Main landing gears aim to reinforce the wing structure or the fuselage structure and the number and location of wheels vary from aircraft to aircraft. Also, depending on the aircraft size and weight, the main landing gear can be accompanied by the rear landing gear, such as in the case of a B-747. Thus, multiple wheels allow distributing the aircraft weight over a larger area. Heavy commercial aircraft usually use four or more wheels on each main gear. Arrangements with more than two wheels per landing gear strut are known as a

bogie. The bogie configuration is a function of the aircraft gross weight and the surface type required to land.

Pavement thickness for a certain aircraft depends on the number and arrangement of the wheels as well as the distribution of the aircraft weight between the nose and main landing gears. In addition, airfield compatibility is an essential issue in aircraft design since pavement bearing strength may vary accordingly with subgrade characteristics and pavement structure configuration. These are factors that determine the number and arrangement of tires needed in a landing gear system. ICAO (2016) provides a standardized international aircraft/pavement rating system known as Aircraft Classification Number (CAN) and Pavement Classification Number (PCN). Basically, the ACN/PCN system indicates that an aircraft having an ACN equal to or less than the PCN can operate on the pavement subject to any limitation on the tire pressure. Numerically, the ACN is two times the derived single-wheel load expressed in thousands of kilograms, where the derived single wheel load is defined as the load on a single tire inflated to 1.25 MPa (Boeing, 1985).

The landing gear design and integration process involve several engineering disciplines such as structures, runway design, and economics, among others. To design and locate a landing gear it is important to know the position of the aircraft center of gravity (CG) and to consider the distribution of the aircraft weight. Usually, between 85 and 92% of the MTOW is supported by the main landing gear. The weight of a landing gear is about 3 to 6% of the MTOW.

A landing gear system is composed by air/oil shock absorbing equipment, wheel and brake assemblies, retraction and safety devices, controls, warning devices, cowling, fairings, support units, gear alignment units, etc. A typical main landing gear of a commercial aircraft is illustrated in Figure 27 with the principal parts identified as an introduction to landing gear nomenclature.

According to Niu (1995), a landing gear designer must select the appropriate number of struts, tire spacing, and tire pressure in order to prevent the trend of increased gross weight that consequently increases the pavement stress.

In addition, conventional landing gears usually are not able to attend the requirements imposed by soft and rough airfield pavements. Soft pavements make it

necessary to provide increased pavement support, and rough pavements require much more shock absorption between the airframe and the surface to keep ground-induced airframe loads at reasonable levels. Williams et al. (1966) argues that the capability of a pavement to support an aircraft (ground flotation) may be improved by employing more tires, larger tires, increased the spacing between tires, reduced tire inflation pressure, or by special tires having wide cross-sections in combination with reduced rim diameters. On the other hand, performance on rough pavements can be improved by using larger tires with smaller rim diameters in order to provide increased working section heights for step bumps or short bump lengths of large amplitude. Long-stroke, double-acting shock struts are essential to alleviate the high tire loads induced by roughness to the level induced by normal operations on smooth pavements.

Figure 27 Nomenclature of the main landing gear bogie truck (FAA, 2012b).

2.4.2 Shock Struts

Basically, there are two types of shock struts also called shock absorbers. Light aircraft usually use shock struts composed by a solid spring such as steel or rubber, while shock struts in heavy aircraft commonly use air or nitrogen combined with hydraulic fluid (oil). Figure 28 compares (from the efficiency and weight standpoints) various types of shock struts in order to illustrate the advantages of the oleo-pneumatic type.

Figure 28 Shock strut efficiency (Niu, 1995).

Besides that oleo-pneumatic have the highest efficiency of all types of shock struts, it also is extremely efficient in terms of energy dissipation. Unlike the steel spring type, oleo-pneumatic type does not store or accumulate the energy, causing the aircraft to bounce down the runway. Typical strut efficiencies, in practice, are between 80 and 90%.

In order to absorb and dissipate shock loads, oleo-pneumatic struts also known as pneumatic/hydraulic or air/oil shock struts, are constructed by two telescoping cylinders as shown in Figure 29. One of them (upper cylinder) is fixed to the aircraft and the other (lower cylinder) works like a piston. As seen in the figure, both of cylinders form two chambers, the lower chamber is always filled with hydraulic fluid and the upper chamber is filled with compressed air or nitrogen. There is an orifice between the cylinders that allow the fluid to pass into the top chamber when the strut is compressed.

Figure 29 Inner construction of a shock strut (FAA, 2012b).

The movement of the fluid during compression and extension of the strut is indicated in the figure by the arrows. The compression begins as the aircraft wheels touch the pavement surface. When the aircraft moves downward, the strut compresses the piston and it is forced upward into the upper cylinder.

The rate of fluid flow between the cylinders is controlled by a conical pin and as a consequence, the heat generated by friction is dissipated through the walls of the strut. Nevertheless, Houbolt, Walls, & Smiley (1955) states that oleo-strut friction is an important factor in the behavior of aircraft taxiing. During taxi operations, the air in the tires and the strut combine to smooth out the effect of pavement bumps.

Thus, the role of the shock absorbing equipment on airfield pavement roughness and aircraft dynamic response is extremely important. It absorbs and dissipates the impact kinetic energy reducing airframe accelerations. Also, the shock strut provides damping to the variety of frequency excitation forces imposed during ground operations.

Touchdown maneuver, for example, is subject to pilot skill, visibility, and turbulence. Thus, a good shock strut design is required to allow for a wide range of landing conditions. Accordingly to Niu (1995), the major consideration to do that is through sink speed (amount of altitude lost over time). In general, normal landings

occur at sink speeds between 0.3 and 1 m/s. Landings above 1 m/s sink speed are usually considered hard landings and occur with diminishing frequency up to 3 m/s. The design case for the landing gear shock struts is 3 m/s for commercial airplanes, but might be greatly increased for carrier-based aircraft or other special types. Consequently, besides absorbing the sink rate energy of the aircraft, the strut should be designed so that the recoil or extension of the strut does not push the aircraft back into the air, producing abnormal bouncing.

Shock absorption in a strut landing gear occurs when the shock energy of landing impact is converted into heat energy. Since shock strut is a hydraulic unit capable to support the aircraft while on the ground and protect the structure during landing, it must be inspected and serviced regularly to ensure proper operation. As stated by Gerardi (1997), improperly serviced landing gear struts can produce unacceptable ground loads into the aircraft as well as those under-serviced can cause pilot lost directional control due to structural failures in the landing gear.

2.4.3 Aircraft Tires

Tires support the aircraft weight, provide the necessary traction for braking and stopping, and absorb part of the shock produced during landing, takeoff, and taxi operations. Since aircraft tires receive several static and dynamic stresses, it must be carefully maintained to perform in a wide range of operating conditions.

Agrawal (1986) states that the aircraft control is influenced by the forces developed in a small area formed when the tire contacts the runway. The magnitude of the forces depends upon a large number of factors associated with the components of the contact area, aircraft tire, braking system, runway surface, and Foreign Object Debris (FOD).

Unlike car tires, aircraft tires are unable to carry loads for long periods of continuous operation. Nevertheless, aircraft tires must be able to operate at high speed even if only for a short time. As stated by FAA (2012b), the deflection capacity into an aircraft tire is more than twice that of a car tire. This enables it to absorb landing loads without being damaged.

Aircraft tires can be classified by type, play-rating, whether they are tube-type or tubeless, and whether they are bias ply tires or radial. The US Tire and Rim Association (TRA) classify aircraft tires in nine types. However, only types I, III, VII, and VIII are still in production. Table 9 describes briefly these types. Dimensions of type VIII tires may be represented in inches or in millimeters.

Bias tires follow the designation nomenclature and radial tires replace the “—” with the letter R. For example, 30 X 8.8 R 15 designates a Type VIII radial aircraft tire with a 30-inch tire diameter, an 8.8-inch section width to be mounted on a 15-inch wheel rim. Additionally, when a B appears before the identifier, the tire has a 60 to 70% wheel rim to section width ratio with a bead taper of 15 degrees, and when an H appears before the identifier, the bead taper is only 5 degrees.

Table 9 Aircraft tire classification by type

Tire Type	Description	Nomenclature (units are in inches)
I	Their design is no longer active. Smooth profile tires that are obsolete for use in modern aircrafts	Only nominal overall diameter
III	Low-pressure tires that have small rim diameters, designed to cushion and provide support from a relatively large footprint. It is typically used on light aircrafts	Two number system with a “—” symbol separating the numbers. The first number is the nominal section width of the tire, and the second number is the diameter of the rim
VII	High-performance tires for jet aircraft. They are inflated to high-pressure and have exceptional high load carrying capability	Two number system with an “X” between them. The first number is the nominal overall diameter of the tire and the second number designates the section width
VIII	Also known as three-part nomenclature tires. Tires inflated to very high-pressure and used on high-performance jet aircraft (very high speeds and very high loads)	Combination of Type III and Type VII nomenclature where the overall tire diameter, section width, and rim diameter are used to identify the tire

Tire plies are reinforcing layers encased in rubber that are laid into the tire to provide strength. Thus, ply rating is used to convey the relative strength of an aircraft tire. As higher the play-rating the tire has high strength and is able to carry heavy loads. The direction of the plies used in the tire construction is another way to classify an aircraft tire. Bias ply tires are used by many aircraft and are characterized by having the angle of the plies between 30° and 60° in relation to the direction of rotation of the tire. Similarly, Radial ply tires are used by modern aircraft. The plies in radial tires are laid at laid at a 90° angle to the direction of rotation of the tire in order to provide sufficient strength to carry high loads with less deformation.

Additionally, the tread of aircraft tires is designed to stabilize the aircraft on the operating surface. The tread is the crown area of the tire that makes contact with the pavement surface. It is made to resist wear, abrasion, cutting, cracking, and heat build-up. Aircraft tire treads for current aircraft have circumferential grooves that allow increasing adhesion to the pavement surface and minimize the risk of hydroplaning in wet conditions. Figure 30 illustrates the aircraft tire treads that are designed for different uses, where (A) is designed for use on paved roads and it is the most common design, (B) is a diamond tread used on unpaved runways, (C) combines A and B and is suitable for all weather conditions, (D) was designed for stopping old and slow aircraft without brakes, and (E) is usually used in nose landing gears to deflect runway water.

Figure 30 Aircraft tire treads for different uses (FAA, 2012b).

Properly inflation is essential to resist wearing and damage and, consequently, it increases the life of the aircraft tire. In commercial aircraft such inflation can vary from about 900 to 1400 kPa (approximately 130 to 200 psi), depending on the aircraft size and weight as well as on the airframe and landing gear configurations. On the other hand, improperly inflated tires increase the potential to fail upon landing due to the high impact loads experienced. Furthermore, Tielking (1989) states that tire stiffness is primarily responsible for non-uniformity in the pavement pressure distribution. In other words, higher inflation pressure results in a stiffer tire and a more non-uniform contact pressure. The author found that the distributions were characterized by reduced pressure along the central portion of the tread, and highest pressure in the shoulder region (near the edges of the tread).

Although aircraft tires can support heavy loads, it also can wear quickly due to the excess of working of the tread produced by the scuffing action along with their outer edges. Contrary to car tires, an aircraft tire that encounters Foreign Object

Debris (FOD) have more risk to cut, snag, or bruise due to its more flexible nature. Moreover, aircraft tires are more susceptible to wear and damage when an aircraft taxiing at long distances or when operating at high-speed. It increases their temperature and for this reason, short taxi distances at moderate speeds are recommended. To minimize tire damage, surface distresses, FOD, and roughness in airfield pavements should be avoided or at least addressed at slower than normal speeds. Nevertheless, tire failures usually occur during takeoff. Tire damage on takeoff is extremely dangerous and most of the time is caused by FOD and heavy braking during aborted takeoffs (see Fig. 31). Preflight inspection of the tires and wheels, as well as maintenance of the pavement surface free of FOD, helps to prevent takeoff tire failure.

Figure 31 Aircraft tire failure due to heavy braking during an aborted takeoff (FAA, 2012b).

2.4.4 Safety Related to Pavement Roughness

Gerardi (1997) states that, although runway roughness problems are generally not a safety issue which threatens the structural integrity of the aircraft, it does happen occasionally. Under ordinary operations, pavement roughness is usually considered as a problem related to ride quality. However, it could be a safety issue in an emergency such as an aborted takeoff situation. In general, aborted takeoff occurs at high speeds and maximum braking effort is used causing the aircraft to pitch forward on the nose gear that exceeding design loads and causing structural failure in their strut, particularly if accumulated fatigue damage had been present. As a result, there is very little nose gear strut stroke remaining to absorb any pavement roughness.

Chai & Mason (1996) consider that a landing gear is an essential intermediary between the aircraft and catastrophe. Figure 32 shows the percentages of fatal

accidents by the phases of flight for worldwide commercial aircraft from 2007 to 2016 (Boeing, 2017). Evidently, high percentages of fatal accidents not only are indicated during the takeoff (6%) and landing (24%), but also during taxi, load/upload, parked, and tow operations (10%). Thus, approximately 40% of the total fatal accidents occur when the aircraft is on the ground.

Figure 32 Percentages of fatal accidents by the phases of flight for worldwide commercial aircraft (Boeing, 2017)

According to Gerardi (1977a), a common problem that can occur during takeoff and taxiing operations is high acceleration levels caused by a rough runway. Due to these accelerations, runways must be evaluated with respect to roughness in order to ensure timely pavement maintenance to control aircraft structural loads and fatigue. Also, rough runways adversely affect the ability of the crew members by reducing instrument readability and crew comfort.

2.4.5 Vertical Accelerations

Kirk (1973) states that vibrations during large aircraft taxiing due to pavement roughness produce airframe metal fatigue damage and dynamic stressing, as well as discomfort for the crew and passengers (anxiety). Also, vibrations of the landing gear cause seal wear with subsequent leakage of air/nitrogen and hydraulic fluid.

In the same context, Ferritto & Forrest (1976) argues that high vertical accelerations, when transmitted to the cockpit, can affect instrument accuracy and decrease the pilot's ability to read the instruments. Schmerl & Zee (1997) considers that rough pavements can also subject the airframe to additional cycles of dynamic loading and increase the need for both airframe and landing gear system

maintenance. Further, the bouncing aircraft increases the dynamic loads on the pavement that accelerates their fatigue.

Houbolt (1961) suggests that vertical accelerations should be less than 0.30 g. The NASA research developed by Morris & Hall (1965a) related to pilot complaints due to runway roughness suggest that the maximum vertical acceleration in the cockpit should not exceed 0.40 g. In contrast, the investigation conducted by Morris & Hall (1965b) showed that accelerations in a cockpit as high as 0.7 g are sufficiently high to produce pilot discomfort and adverse effects on the precision of takeoff. However, Alford (1972) argues that vertical accelerations exceeding 0.33 g are unacceptable and 0.5 g levels seriously affect pilot performance. As a consequence, Sonnenburg (1976) states that, for both theoretical and experimental data, a few isolated runway pavement sections reaching or exceeding 0.40 g claims to be rough by pilots.

For Seeman & Nielsen (1977) runways with RMS acceleration values between 0.10 and 0.15 g are relatively smooth, and those with values greater than 0.20 must be considered rough. Since the 70s, a value of 0.40 g has been used to identify acceptable limits of vertical accelerations on military aircraft. Horn (1977), for example, used the 0.40 g value as a limit of tolerable vertical accelerations. This criterion was also based on human tolerance to vibration (Figure 33). Tests performed by NASA (1992) also supported this value because they have documented that human tolerance to vertical acceleration lies in the range of 0.35 to 0.40 g.

Figure 33 Human tolerance to vertical vibration (Spangler & Gerardi, 1993)

ISO (1997) also gives approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport, as an analogy. In this case, the reactions at various magnitudes depend on passenger expectations with regard to trip duration and the type of activities passengers expect to accomplish (e.g. eating, reading, writing, etc.) and many other factors (acoustic noise, temperature, etc.). Table 10 shows these reactions and their correspondent vibration environment, expressed in g.

Table 10 Subjective reactions to vibration in public transport (ISO, 1997).

Vibration environment (g)	Subjective reactions
Less than 0.032	Not uncomfortable
0.032 to 0.064	A little uncomfortable
0.051 to 0.102	Fairly uncomfortable
0.082 to 0.163	Uncomfortable
0.127 to 0.255	Very uncomfortable
Greater than 0.204	Extremely uncomfortable

Spangler & Gerardi (1993) states that the most obvious runway roughness criteria would appear to be associated with the levels of vertical acceleration imparted to the pilot at the aircraft cockpit. These criteria were advanced by Gerardi (1997) whom related accelerations computed at the aircraft cockpit to human acceleration tolerance limits established by Harris & Piersol (2002). Based on this reference, the cockpit acceleration limit of 0.35 g has been suggested for measuring runway profile roughness. As noted in Figure 33, the tolerance level is fairly constant over a range of frequencies. Ferritto & Forrest (1976), also states that an acceptable standard for runway roughness is to limit vertical accelerations to 0.40 g. However, there is a need to standardize the criteria used to define unacceptable levels of roughness.

Lee & Scheffel (1968) found that satisfactory runways for piston-engine aircraft were causing undesirable vertical accelerations in the cockpit of newer, faster, and heavier aircraft. Thus, for a given velocity over a given runway roughness pattern, aircraft of different sizes will respond in different ways. This response depends on the response frequency (f , in cycles per second) of the aircraft. So, a bump of given height and length will amplify the regular oscillatory up and down motion of the aircraft maximizing the cockpit acceleration to undesirable levels. According to the authors, data from NASA investigations shows that the response frequency is lower for heavy aircraft. Figure 34 shows the relationship between frequency response and

takeoff speeds, where for a given velocity, bump lengths increase as the response frequency decreases. Also, for a given frequency the bump lengths increase with increasing velocity. Response frequencies vary from 2 cps to 3 cps for relatively light fighters to below 0.5 cps for large aircraft.

Figure 34 Bump length variation versus speed for several frequencies (Lee & Scheffel, 1968).

A study conducted by Hall (1969) measured cockpit normal and lateral accelerations, and center of gravity normal acceleration in a long-range jet with MTOW about 150 ton. The author observed that the level of vibration increased as the aircraft speed increased. The largest acceleration level in the cockpit was 0.46g and the largest near the center of gravity was 0.17g. The maximum acceleration occurred during a take-off run and was approximately four times the RMS acceleration. The author concluded that the frequency and amplitude of the accelerations depend upon the aircraft weight, their operational speed, and the pavement elevation profile.

Similarly, Mitchell (1970) measured vertical accelerations at the cockpit of a Boeing 707 (MTOW about 142 ton) during 94 takeoffs from 31 airports. The maximum cockpit acceleration measured was 0.75g. For 10% of the takeoffs the

maximum cockpit acceleration exceeded 0.53 g and for another 10%, the accelerations were greater than 0.32 g. These results made the author conclude that the amplitude of the accelerations in an aircraft cockpit varies from airport to airport and a certain aircraft weight. In the study, the variation between airports was by a factor of two at a weight of 115 ton. At a given airport, the response at a weight of 140 ton was twice that at 90 ton. In addition, the author observed that accelerations at the center of gravity did not vary with aircraft weight. However, the cockpit/center of gravity acceleration ratio increased with increasing weight. This ratio was between 0.9 and 2.3, but for more than 80% of the takeoffs, the ratio was between 1.0 and 7.5. Thus, accordingly with the author, no airport was outstandingly bad, but one airport caused larger peak accelerations than any other.

In line with Mitchell, Hutton (1971) made an analysis of vertical accelerations during 25 takeoffs and landings from 20 airports. Results showed that the acceleration intensity was 40% greater in the landing than the takeoff. However, the author argues that the effect of this on the crew is most probably offset by psychological demands upon them being less severe during the landing than the takeoff.

According to Morris (1970), studies of roughness problems faced during takeoff, landing, and taxiing indicated that a pilot's classification of a runway as satisfactory or rough depends on the magnitude and number of responses and their occurrence relative to critical procedures and aircraft operations. Also, the acceleration level accepted by a pilot without calling a runway rough depends on the aircraft type. The author argues that cockpit accelerations of 0.40 g generally are intolerable. Large aircraft responses in the study were generally associated with runway roughness characterized by bump heights between 1.5 and 8 cm for bump lengths up to 76 m.

As stated by Gervais (1991), several computer simulations derived from U.S. Air Force flight tests indicated that some runways can be much more damaging to the aircraft than what is normally expected and designed for aircraft service life. As seen in Figure 35, the effects of fatigue on an aircraft are exponential. Note that vertical acceleration of 0.55 g can be one thousand times more damaging than the design acceleration of 0.35 g for takeoff and landing.

Figure 35 Effect of runway roughness accelerations on aircraft fatigue (Gervais, 1991).

Gerardi (1997) studied the effect of aircraft response to long wavelength roughness through the construction of several bump configurations of 90 m in length and 6 to 8 cm in height. A heavy aircraft was simulated traversing the three bump configurations at speeds from 20 to 140 knots (37 to 259 km/h – rotation velocity –). Results showed unacceptable aircraft response about 0.70 g at higher speeds of 90 to 130 knots (167 to 241 km/h). As a consequence, the author concluded that runway roughness assessment should be based on aircraft dynamic response.

However, according to Milwitzky (1959), theoretical studies on landing gear dynamics have shown that for a wide range of aircraft, regardless of size, the predominant response of the landing gear generally occurs between 1.5 and 2 cycles per second. It is due to the standardized way in which tires are specified and shock strut compression ratios are normally chosen. Thus, critical runway wavelengths corresponding to operational speed ranging from 20 to 130 knots (37 to 241 km/h) are between 5 and 45 m.

2.4.6 Landing Gear Pavement Loads

According to Mikhail & Mamlouk (1997), airfield pavements are complicated physical structures responding in a complex way to the influence of several variables, such as dynamic loads, materials, and environmental conditions. Upon that, modern heavy aircraft with high gross weights and tire pressures results in faster and more severe damage to pavements. Different from other structural systems, airfield pavement has a relatively short service life and deteriorates rapidly because of dynamic loads and environmental effects.

Aircraft loads are the science of determining the loads that an aircraft structure must be designed to support. Basically, aircraft loads are those forces applied to the aircraft structural components to establish the strength level of the complete aircraft. It may be caused by air pressure, inertia forces, or reactions during ground operations. The study of the behavior of these forces is the subject of aerodynamics.

For Hardrath (1965) the most important factors that influence the fatigue life of aircraft structures are the accumulation of damage (number and severity of loads) under the complex loadings encountered in service, the rate of fatigue crack propagation, and the residual static strength.

Horn & Ledbetter (1975) and Ledbetter (1975 and 1976) studied the relationship between the responses of flexible and rigid runway pavements to static and dynamic loads. The study also involved crucial elements such as the determination of the magnitudes of the dynamic loads, determination of the depths of pavement structures affected by both types of loads, and the investigation of the relationship between aircraft speeds and dynamic loads. Two series of tests were conducted, one during cold weather (2 to 13°C) and the other during warm weather (29 to 47°C).

Both flexible and rigid runways (with surfaces relatively smooth) were instrumented to measure and record pavement responses to aircraft loads. Aircraft B-727-100 (MTOW about 73 ton) and C-880 (MTOW about 88 ton) were instrumented for both series to measure the aircraft wheel loads transmitted to the pavement structures during normal aircraft operations. Data were collected for the following basic aircraft modes of ground operation: creep-speed taxi (3 to 8 knots – 6 to 15 km/h), low-speed taxi (15 to 30 knots – 28 to 56 km/h), medium-speed taxi (45 to 80 knots – 83 to 148 km/h), high-speed taxi (85 to 130 knots – 157 to 241 km/h), high-speed braking (130 to 45 knots – 241 to 83 km/h), takeoff rotation (85 to 130 knots – 157 to 241 km/h), touchdown, high-speed braking with reverse thrust, and turning (4 to 30 knots – 7 to 56 km/h).

Results showed that dynamic loads were about 1.2 times greater than static loads and no basic operating mode induced pavement responses greater than those occurring for static load conditions. Also, extrapolation of the test results indicated

that for both pavement types in cold weather, large dynamic loads could possibly produce responses larger than static loads. Consequently, Horn and Ledbetter conclude that, based upon gradually reduced elastic and inelastic response with high speeds, pavement thickness can be reduced in the interior of runways.

However, due to the high loads and to prevent excessive deterioration in turn areas, exit areas of runways should be more robust than the main runway flexible pavement, mainly due to tangential strains. In addition, the flexible pavement structure layer at a depth of 1 to 1.3 m was less than 10% of the surface response to the various modes of aircraft operation. Similarly, the rigid pavement structure layer at a depth of 0.40 to 0.60 m responded to about 30% of the surface response. These were the deepest layers monitored during dynamic load tests for both pavement structures.

In line with FAA (1970), there are two principal effects that influence pavement response to dynamic loads. The first is the increased aircraft wheel loads resulting from modes of operation, roughness, and aircraft structural characteristics during ground operations. The second is the dynamic load phenomena associated with the materials used in the construction of rigid and flexible pavements.

Airfield pavements must be capable to sustain wheel loads arising from various basic types of aircraft ground operations. Accordingly to FAA, these loads can range from a value less than the aircraft static load to 2.3 times the static load, as shown in Table 11. Also, Caldwell, Gerardi, & Borowski (1979) agree that dynamic main gear loads can be as high as 2.5 times the corresponding static aircraft loads.

Similarly, Niu (1995) comments that a landing gear load factor can be determined dividing dynamic loads by the static loads. Its magnitude is usually determined by the airframe structure design requirements. According to the author, load factors generally vary from 0.75 to 1.5 in large aircraft, to 3.0 in small aircraft, as shown in Figure 36. For this reason, shock strut design must avoid exceeding their correspondent Load Factor; otherwise, the structural integrity of the airframe can be in danger.

Table 11 Airport load factor for basic ground operations (FAA, 1970)

Type of load	Relation to static load
Parked (static load)	1.0
Low-speed taxi	1.3
Turning	1.6
Low-speed breaking	1.3
Accelerated takeoff roll	1.2
Aborted takeoff / High-speed breaking	2.3 (for nose gear)
Takeoff rotation	1.8 (for negative-lift aircraft)
Landing impact	< 1.0
High-speed breaking	2.3 (for nose gear)
Decelerated landing rollout	1.2

Figure 36 Landing gear load factor comparison (Adapted from Niu, 1995)

According to Mikhail & Mamlouk (1997), the variation in dynamic loads occurs instantaneously above and below the static weight because of the aircraft-pavement interaction including pavement roughness, landing gears configuration, struts type, tire type, and operational speed.

In this way, Schmerl & Zee (1997) suggest that pavement engineers must minimize aircraft fatigue by constructing and maintaining smooth pavements and reducing the unnecessary stress inflicted by rough pavements. In addition, Pavement roughness can be a safety issue for aircraft operating close to their maximum weight because they have used up most of the strut stroke and tire stroke just to carry the static loads. Under-serviced struts are also another factor that contributes to premature failures and fatigue incidents. Woelfl (1980; 1981) argues, for example, that rapidly repaired bomb-damaged runways indicate unusually high dynamic loads due to increased pavement roughness of the repaired runway. These dynamic loads are generally higher than static loads.

As stated by Gerardi (1977b), aircraft fatigue life is primarily based on the number of Ground-Air-Ground (GAG) cycles expected during the life of an aircraft (Fig. 37). Dynamic loading due to pavement roughness is one of the principal factors used to determine the number of GAG cycles. In order to avoid significant reduction of aircraft fatigue life, the magnitude and frequency of the dynamic loads should not be underestimated.

Figure 37 Ground-Air-Ground cycle (Batchu, 2018)

According to FAA (1994), the condition of the runway surface can have a significant effect specifically on takeoff performance, since it can affect both the acceleration and deceleration capability of the aircraft.

Gerardi (1997) states that rough runways reduce stopping ability and, consequently, can increase the braking distance by about 50%. During landing on rough runways, aircraft dynamic loads affect the pilot's ability to maintain constant brake pressure. It made the aircraft bouncing up and down in two ways: (1) when the aircraft bounces up there is less weight on the wheels, therefore resulting in less drag load from the braking action, and (2) when the aircraft is on the downside of the bounce, the added tire deflection can send a false speed indication to the antiskid system, since the speed calculation is based on tire diameter. Additionally, stopping distance can be considered even more critical if aircraft operates on pavements with FOD due to the reduction of surface friction characteristics.

In this context, there is a need of current aircraft require a pavement system structurally capable of supporting gross loads around 600 ton. Therefore, pavement surface must provide adequate skid resistance and must be of sufficient smoothness to prevent undue loss of fatigue life in the aircraft, since emphasis has been placed upon the comfort and safety of aircraft ground operations and other factors related to the interaction between the pavement and the aircraft.

Summarizing, aircraft dynamic response to pavement roughness is highly dependent on aircraft parameters such as gear stiffness, gear spacing, the degree of coupling between the rigid body modes of vibration, and roughness severity (Gerardi, 1977b). Thus, aircraft response properties must be categorized according to the aircraft type (weight), landing gear configuration, taxi speed, and runway profile (Sonnenburg, 1976).

2.5 PROFAA SOFTWARE

Gerardi & Lohwasser (1973; 1974) developed the first computer program to determine the dynamic response of an aircraft to runway roughness during takeoff and constant speed taxi. This program was named TAXI and their mathematical model was programmed in FORTRAN for a CDC 6600 digital computer (the world's fastest computer from 1964 to 1969).

Nowadays, the current Profile Federal Aviation Administration software (ProFAA) was designed to analyze pavement longitudinal elevation profiles, to compute several pavement roughness indexes, and to simulate aircraft dynamic response of representative commercial aircraft in terms of weight. Besides calculating IRI and BBI indexes, the ProFAA software allows computing another roughness indexes such as Straight Edge, California-type Profilograph Profile Index (PI), and RMS Band-Pass Index (objective measure for Ride Number computation). Furthermore, simulations of aircraft response include Root Mean Square (RMS) vertical accelerations at the cockpit and center of gravity and dynamic strut loads at the nose, main, and rear landing gears.

ProFAA is a Visual Basic (VB6) program available to the public at no charge with access to the source code for local modification (Larkin & Hayhoe, 2009). However, there are many troubles when modifying the source code, because most of the variables are not totally described. The software package is available for free download from <http://www.airporttech.tc.faa.gov> and the last version was launched on July 27, 2017.

The program was written to provide information related to ride quality and potential aircraft structural damage. New pavement acceptance and quality control can be assessed by physical and rolling straightedge simulations (with a deviation between supports or over a full length) and/or by a profilograph simulation. The aircraft response (pitch and bounce) can be simulated and RMS acceleration output for ride quality evaluation. In addition, a Boeing Bump Method analysis can be performed through the BBI index that normalizing the Boeing threshold for an excessive potential of structural damage being caused to an aircraft traveling on a runway.

According to Hayhoe (2007) the principal features including in ProFAA are:

- Index Computations (PI, BBI, IRI, Band-Pass Index, and Straightedge Index),
- Four representative aircraft types (B-727, B-747, DC-9, and DC-10),
- Displays of the profile and index computations over the full length of the profile, with zoom capability,
- Display of the index values over user-selectable section lengths,

- Display of probability distributions (percent exceedances) for straightedge and BBI, and
- English or Metric units

Figure 38 shows a screenshot of ProFAA with a profile measured at a small airport displayed in the picture box at the top pane. Note that five picture boxes are used to plot the roughness index component values along the pavement. The second pane shows the maximum deviation from a 4.9 m straightedge, the third the BBI, the fourth the rectified slope computed from the IRI quarter car simulation, the fifth the vertical follower wheel motion computed from the profilograph simulation, and the sixth the bandpass filter output. A profile may also be zoomed to examine details throughout its length and cut it to analyze isolated features.

Figure 38 Screenshot of ProFAA showing a pavement profile and the computed roughness indexes

Similarly, Figure 39 shows the same screenshot for the same profile but now plotting the aircraft dynamic response. The second pane in the figure shows the vertical accelerations at the center of gravity of a B-727 aircraft traversing the

pavement profile at 100 knots (185 km/h). The third pane shows the vertical accelerations at the cockpit, the fourth the nose gear pavement loads, and the fifth the main gear pavement loads. The sixth pane is only available for the simulation of the B-747 rear gear pavement loads.

Figure 39 Screenshot of ProFAA showing a pavement profile and the computed dynamic response

Figure 40 shows the bar chart for the BBI averaged over 100 m sections. As seen in the figure, also other index charts and the simulation charts can be visualized. The numerical values are also output to a text file or another format types.

Pressing the In/Out button at the top left allows probability distribution functions (PDFs) to be displayed for the BBI values. Figure 41 shows the PDF for the BBI. From the figure, 90% of the BBI values are less than 0.34 and the largest value is 1.53. The figure also shows other parameters values that can be changed according to the user preferences, as described below.

Figure 40 Bar chart showing BBI values averaged over 100 m section lengths

Figure 41 Probability Distribution Function of the BBI

- Sample Spacing is the interval between the profile samples. Since the required sample spacing for ProFAA is 25 mm this value cannot be changed,
- Averaging Distance is the section length used to calculate the index values. It can vary from 30 to 1200m. The default section length is 304.8m for all except for the PI calculations which are over section lengths of 152.4m.
- Smoothing Distance is the smoothing distance at the profile ends when “Smooth Ends” box in Figure 39 has been checked. It can vary from 30 to 610m,
- Straightedge Length is the portion of the straightedge length over which the maximum deviation is determined. For full length, the maximum deviation is found over the full length of the straightedge. For between, the maximum deviation is found over the length of the straightedge between the support points. It can vary from 1.5 to 457m and the default value is 4.9m,
- Aircraft Speed is the aircraft longitudinal speed in the aircraft simulation. The unit is in knots and can vary from 10 to 200 knots (19 to 370 km/h),
- Airframe Damping Factor is the damping factor of airframe vibration. It can vary from 0 to 0.1. Damping factor 0.025 is suitable for the aircraft library (refer to Annex B),
- Aircraft Type is the aircraft used in the aircraft simulation (a list with the four aircraft appears when clicking on this button),
- Number of Modes is the number of the vibration modes used in the aircraft simulation. It can vary from 1 to 10.
- Cutting Length at Ends is the deleting length at the profile ends in index calculation. It can vary from 0 to 300m,
- Section Length for CA PI is the section length used to calculate CA profilograph index values. It can vary from 100 to 200 m,
- Bandpass Lo Cutoff is the low cutoff frequency used by the Band-Pass Index. It can vary from 0.06 to 304.8 m/cycle and the default value is 7 m/cycle, and
- Bandpass Hi Cutoff is the high cutoff frequency used by the Band-Pass Index. It can vary from 0.03 to 152.4 m/cycle and the default value is 2 m/cycle.

In line with FAA (2004), to successfully read an elevation profile in ProFAA the input data file must have the following format:

- One elevation profile per file,
- Elevation numerical values stored in sequence as single point numbers,
- Implied sample spacing of 25 mm.
- Longitudinal distance is not stored in the file.
- The required file extension is .pro (the format used by ProFAA).

As stated by FAA (2009), The ProFAA package includes an additional program called “Convert Profile Format”. This Visual Basic program was developed for converting text-based elevation profile files (.txt) with arbitrary sample spacing to .pro files and for converting .pro files to .txt files. However, there are another input and output formats associated with ProFAA:

- ERD: file format for storage and analysis of road profiles, developed by the Engineering Research Division of the University of Michigan Transportation Research Institute (UMTRI),
- ASTM: format used by the ProVAL software for highway pavement roughness evaluation. This format is specified in the ASTM Standard “Specification for Data Format for Pavement Profile” (ASTM, 2017d)
- Text (.txt) – numerical values in a single column (Carriage Return Line Feed – CRLF delimiters) of ASCII numerical values representing elevation values at constant sample spacing.
- CSV – output format in which each numerical value is separated by a comma (comma delimited list of ASCII) representing elevation values at constant sample spacing.

3 METHODOLOGY AND DATA

The main objective of this research is to evaluate the effect of airport pavement roughness on aircraft dynamic response in terms of vertical accelerations and dynamic loads, which may compromise the aircraft safety and the pavement performance.

To reach this main objective it is necessary to achieve four secondary objectives. The first one is to compare currently used pavement roughness indices IRI and BBI. The second one is to compare vertical accelerations produced at the cockpit with those produced at the center of gravity, as well as between dynamic pavement loads at the nose and main landing gears as well as at the rear landing gear of a large commercial aircraft. The third one is to correlate pavement roughness indices with aircraft dynamic responses by taxi speed and aircraft weight. Finally, the fourth one is to identify critical limits based on excessive response and propose alternative classifications for airport pavement roughness evaluation based on critical aircraft dynamic responses. A work plan for meeting these objectives is developed in the following paragraphs.

3.1 PAVEMENT ELEVATION PROFILE DATA

A large database with 236 real world airport pavement profiles was set up. The profiles were obtained from the official FAA website www.airporttech.tc.faa.gov (FAA, 2018). Although the profiles have been labeled by a three-letter code, it was not possible to identify their geographical location, probably due to confidential reasons. However, there is sufficient information since it is known the profile length and elevations along them with a survey interval of 25 mm.

The survey interval indicates that the profile measurement was conducted by an inertial profiler. It is important to note that the sample interval is not a barrier to compute the BBI since after the elevation profile has been read into ProFAA, the software low-pass filters it with a sixth-order Butterworth filter at a cutoff frequency of 2.0 cycles/m and takes every fourth sample to give the required sample spacing of 25 cm.

The overall IRI was computed for all full-lengths profiles in order to perform a stratified sampling that defined the profiles used for the simulation of the aircraft dynamic responses. The stratified sampling was based on the overall IRI of each profile.

Once a critical IRI limit commonly used in airport pavements is equal to 2.5 m/km (ANAC, 2019), a five-category classification based on this limit is created to serve as a reference for the analyses performed in this research (see Table 12). However, it may not represent common critical IRI values found in highway pavements. Furthermore, it is important to highlight that this classification is proposed only for a guide to conduct the analyses carried out in this research without the intention to impose or substitute any existent official criteria and/or classification.

Table 12 Proposed classification based on the critical IRI limit of 2.5 m/km adopted from ANAC (2019)

Category	IRI (m/km)
Very Good	< 1.0
Good	1.0 to 1.5
Regular	1.5 to 2.0
Poor	2.0 to 2.5
Very Poor	> 2.5

Therefore, all the 236 profiles were classified based on the classification above and a cut-off limit of 4.0 m/km was also considered. The cut-off limit was established in order to select profiles with roughness levels that are usually encountered in most airport pavements. After this process, only two profiles did not fit the classification.

Then, the 234 preselected profiles were divided into sections of 100 m in length and computed the correspondent IRI values by section. The objective was to identify those profiles with the best IRI-Section distribution respect to the IRI-Profile. After this step, 41 profiles were selected.

Finally, a representative random sample of 20 profiles was finally chosen. Table 13 shows the length of each profile and their IRI Profile, which was also calculated by ProFAA. The profiles chosen totalize approximately 57,000 linear meters of runway pavement resulting in 570 pavement sections of 100 m in length. Appendix A presents the pavement elevation profiles used in this research.

Table 13 Airport pavement elevation profiles used in this research

Profile Number	Length (m)	IRI Profile (m/km)	IRI Category
1	3100	0.2	Very Good
2	2600	0.6	Very Good
3	1500	0.8	Very Good
4	1800	1.0	Good
5	3200	1.0	Good
6	1800	1.1	Good
7	2800	1.2	Good
8	3900	1.3	Good
9	3700	1.4	Good
10	3200	1.5	Regular
11	3200	1.6	Regular
12	3100	1.8	Regular
13	3800	2.1	Poor
14	2800	2.1	Poor
15	2700	2.3	Poor
16	2200	2.3	Poor
17	3700	2.5	Very Poor
18	1800	2.6	Very Poor
19	3400	2.7	Very Poor
20	2700	2.9	Very Poor

3.2 PAVEMENT ROUGHNESS INDICES ANALYSIS

IRI and BBI were computed by ProFAA according with the following process. Firstly, IRI and BBI indices were computed for each full-length profile, naming them as *IRI Profile* and *BBI Profile*, respectively. Secondly, the profiles were divided into three sections (first third, middle third, and last third) and new IRI and BBI indices were computed calling them *IRI Thirds* and *BBI Thirds*, respectively. Finally, the profiles also were divided into sections of 100 m in length and computed their individual new IRI and BBI values, which were called *IRI Sections* and *BBI Sections*, respectively. Thus, comparisons between pavement roughness indices were conducted by classifying all the profiles into three samples: *Profile*, *Thirds*, and *Sections*.

The first step in the analysis of IRI and BBI was to present their descriptive statistics, histograms and tests of normality; and to perform correlations between them for the samples *Profile*, *Thirds*, and *Sections*. The second step was to analyze peak (MAX) and average (RMS) values in the database and correlations were also performed. Finally, the third step was to carry out a linear regression analysis for IRI and BBI as independent and dependent variables, respectively. However, it is important to note that IRI and BBI variables were transformed to improve the

normality of the data, but the coefficients are been presented in the original form. IRI and BBI results can be consulted in Appendix B.

3.3 SIMULATION CRITERIA

Specific parameters in ProFAA must be designated by the user in order to establishing the input for aircraft dynamic response simulations. The inputs used in this research are detailed bellow.

a) Aircraft Type

The ProFAA software provides a default library with four representative aircraft based on MTOW to simulate aircraft dynamic responses. Although most of them are no longer in operation, they approximates to the behavior of analogous aircraft once aircraft dynamic response depends predominantly on aircraft weight, axle spacing, landing gear configuration, and operational speed.

This approach allows the estimating of the dynamic response produced in similar or analogous aircraft that are currently in operation. Thus, simulations were carried out according to the four aircraft classes presented in Table 14. Each class is represented by an aircraft of the ProFAA library and can involve analogous aircraft with similar weight and landing gear configuration. Dimensions and characteristics of both representative and analogous aircraft are detailed in Appendix C.

Table 14 Aircraft classes			
Class	Weight Group (kg)	ProFAA Representative Aircraft for Simulations	Current Analogous Aircraft
I	Less than 70,000	DC-9-41	E-190 AR
II	70,000 – 140,000	B727-100	B737-800 / MAX 8
III	140,000 – 210,000	DC-10 CF	B767-300 ER
IV	Greater than 210,000	B747 SP	B747-400

b) Aircraft Speed

Ten constant operational speeds ranging from 20 to 200 knots (37 to 370 km/h) were considered for this study. The speeds are 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 knots and were discretized based on the classification shown in Table 15:

Table 15 Constant operational speed classification

Category	Speed (knots)	Speed (km/h)
Very Low	20 and 40	37 and 74
Low	60 and 80	111 and 148
Medium	100 and 120	185 and 222
High	140 and 160	259 and 296
Very High	180 and 200	333 and 370

Note that taxi constant speed means that a given aircraft is on the ground and traverses the entire elevation profile at the same speed. Therefore, the simulations carried out in this research do not consider acceleration and deceleration behavior nor the effect of landing and takeoff operations because the software ProFAA does not allow this type of analysis.

In this context, simulations in ProFAA were carried out by representative aircraft class attending the parameters listed in Table 16:

Table 16 Values of parameters used in aircraft dynamic response simulation

Parameter	Value
Sample Spacing, m	0.0255248
Averaging Distance, m	100.00
Smoothing Distance, m	100.00
Aircraft Speed, knots	20 - 200
Airframe Damping Factor	0.0250
Aircraft Type	DC-9 / B-727 / DC-10 / B-747
Number of Modes	10
Cutting Length at Ends, m	0.00

3.4 AIRCRAFT DYNAMIC RESPONSE ANALYSES

Pavement-aircraft interaction is studied through the use of computer modeling. The elevation data from the 20 selected pavement profiles were entered as input into the software ProFAA to simulate aircraft dynamic responses. Five responses are divided as output:

- Vertical Acceleration at the Cockpit (VACP)
- Vertical Acceleration at the Center of Gravity (VACG)
- Dynamic Pavement Loading at the Nose Gear (NGPL)
- Dynamic Pavement Loading at the Main Gear (MGPL)
- Dynamic Pavement Loading at the Rear Gear (RGPL) – only for the aircraft Class IV (B-747) which have a rear landing gear that complements their main landing gear.

Simulations of aircraft dynamic responses were carried out only for the *Sections* sample and for each aircraft class (four classes) traversing each elevation profile (20 runways) at each discrete speed (37 to 370 km/h – 20 to 200 knots). Furthermore, aircraft dynamic responses variables were transformed to improve normality of the data and MAX and RMS values were also considered in the analyses. Some examples of data output from ProFAA program are given in Appendix D.

The first step was to present descriptive statistics, histograms and tests of normality for vertical accelerations and pavement loads. Pavement loads were presented in terms of the static ratio. This ratio was determined by the relation between dynamic gear pavement loads (obtained through ProFAA simulations) and maximum static pavement loads (based on “Official Airplane Characteristics for Airport Planning) for a certain representative aircraft type. Further information about aircraft characteristics (landing gear configurations, aircraft tires, maximum pavement loads, etc.) can be found in Boeing (1984a; 1984b; 1985; 2002; 2004; 2005; 2013; 2018), Embraer (2015), as well as in Appendix C.

The second step was to correlate VACP vs. VACG and NGPL vs. MGPL; NGPL vs. RGPL; and MGPL vs. RGPL. Correlations were also conducted for both overall data and by aircraft class. The third step was to carry out linear regression analysis for vertical accelerations and pavement loads where VACP and NGPL were independent variables, respectively, except for MGPL vs. RGPL where the independent variable was MGPL. It is important to note that vertical accelerations and pavement loads variables were transformed to improve normality of the data. However, the coefficients have been presented in the original form. The fourth step was to analyze vertical accelerations and pavement loads from an aircraft speed point of view. Results were presented by maximum values and also by aircraft class.

Finally, the fifth step was to analyze vertical accelerations and pavement loads based on IRI as independent variable. Here, maximum values were represented graphically while RMS values were presented numerically through tables. Values were also presented by aircraft class and separated by speed category. Furthermore, a summary of the results for vertical accelerations and pavement loads was also presented. Appendix E provides complementary graphics regarding these analyzes.

3.5 STATISTICAL COMPARISONS

In this section aircraft dynamic responses were correlated with pavement roughness indices which were considered as independent variables. Then, linear regression analyses were carried out by overall, RMS, MAX, and aircraft class data. Once all the variables were transformed to improve data normality, coefficients were presented in the equation form in order to obtain directly the correspondent estimated value. Correlations and regressions are presented according to the following sequence:

VACP vs. IRI	NGPL vs. IRI	RGPL vs. IRI
VACP vs. BBI	NGPL vs. BBI	RGPL vs. BBI
VACG vs. IRI	MGPL vs. IRI	
VACG vs. BBI	MGPL vs. BBI	

Results are presented in separated tables where the last two columns corresponds to the IRI and BBI estimated when vertical accelerations reach 0.35 g and 0.40 g and when pavement load ratios reach 1.5 and 2.0, as the case may be. This approach allowed identifying the lower values that reached these limits and consequently were considered critical values. Thus, at the final of the section, it is presented two additional tables that summarize these critical models, one for vertical accelerations and the other one for pavement loads.

Further information about the method used to improve data normality as well as the statistical approach used to conduct correlations and regression analyses can be found in Appendix F.

3.6 CLASSIFICATIONS BASED ON AIRCRAFT DYNAMIC RESPONSES

This section presents alternative classifications to assess airport pavement roughness based on aircraft dynamic responses. All the classifications were based on IRI since this was the index that showed greater compatibility with the responses.

This section comprised three steps. Firstly, two classifications, called “current classifications” are presented as a reference. The first classification, called SAYERS, is based on the critical limit suggested by Sayers & Karamihas (1998) that is 2.0 m/km. The second classification, called ANAC, is based on the critical limit indicated by the National Civil Aviation Agency of Brazil (ANAC, 2019) that is

2.5 m/km. Secondly; three alternative classifications are proposed based on the limits established by the critical models identified before.

Thirdly, a case study is presented (in a separate chapter) as an application example. The case study consists of IRI reports for an airport network composed by 9 operational runways divided into several sections of 100 m in length. The runways are constructed of asphalt concrete and most of them are located in a tropical region with average temperatures above 32° C. The average elevation of the runways is 21 m, but there is a runway located at about 800 meters above sea level. All the runways belong to international airports of medium and large sizes.

The runways are presented separately in tables. Each table illustrates the five IRI classifications (current and alternative) and also shows the estimated parameters BBI, VACP, VACG, NGPL, MGPL, and RGPL that are determined by the correspondent equations given by the critical models. Furthermore, a summary of the five classifications are provided.

A colored scale is used to identify each IRI category in the classifications. The colors range is the same for all the classifications (see Table 17).

Table 17 Colored scale for IRI categories

IRI
Very Good
Good
Regular
Poor
Very Poor

Finally, another table is created to show the number of pavement sections that fall into each IRI category for both current and alternative classifications, as well as the corresponding percentage compared to the total sections in the network.

4 DATA ANALYSIS AND DISCUSSION

This chapter presents the pavement roughness data, the aircraft dynamic response simulation results, the analysis of the interaction between the two and the proposal of alternative classifications for airport pavement roughness evaluation. The chapter is divided into seven major sections, as listed below, and each section provides a brief analysis of the graphical information presented and a detailed discussion of the findings.

- 1) Pavement Roughness Indices (IRI vs. BBI);
- 2) Aircraft Dynamic Responses (VACP, VACG, NGPL, MGPL, and RGPL);
- 3) Aircraft Dynamic Responses vs. Speed;
- 4) Aircraft Dynamic Responses vs. IRI;
- 5) Statistical comparisons;
- 6) Alternative airport pavement roughness classifications; and,
- 7) Case study.

4.1 PAVEMENT ROUGHNESS INDICES

As described in Chapter 3, twenty runway pavement elevation profiles were used in this study. IRI and BBI indices were computed according to the three following samples:

- 1) Profile sample (full length index values);
- 2) Thirds sample (index values by thirds); and,
- 3) Sections sample (index values by sections of 100 m in length)

4.1.1 Statistics

Tables 18 and 19 provide a summary of the descriptive statistics for IRI and BBI indices, in terms of *Profile*, *Thirds*, and *Sections* samples. As shown in Table 18, IRI values ranges from 0.1 to 3.9 m/km, the mean values are about 1.7 m/km, and the standard deviation is 0.8. In general, skewness and kurtosis values indicate that the data is slightly skewed left and platykurtic. Figure 42 shows the histograms for the IRI values and allow visualizing the data distribution.

As can be seen in Table 18, the *IRI Profile* sample is small (one index value per profile, $n=20$). Through the histogram, is evident that the *IRI Profile* sample does not contain enough values to accurately show a normal distribution of the data. The same occurs for the *Thirds* sample, but now their histogram shows two large peaks that also suggest non-normality. Conversely, *IRI Sections* (with $n=570$) seems to have sufficient data that approximates to a normal distribution. Although Sections sample there is no significant outliers, the histogram evidences multiple peaks or modes that also suggest that the IRI data is not normal.

Table 18 Descriptive statistics of IRI for *Profile*, *Thirds*, and *Sections* samples

Statistics	IRI Profile	IRI Thirds	IRI Sections
n	20	60	570
Mean	1.65	1.65	1.67
Std. Error of Mean	0.17	0.10	0.03
Median	1.55	1.55	1.60
Mode	1.00 ^a	1.10 ^a	1.10
Std. Deviation	0.76	0.77	0.79
Variance	0.58	0.60	0.62
Skewness	-0.05	-0.05	0.14
Std. Error of Skewness	0.51	0.31	0.10
Kurtosis	-0.96	-.20	-0.60
Std. Error of Kurtosis	0.99	0.61	0.20
Range	2.70	3.00	3.80
Minimum	0.20	0.20	0.10
Maximum	2.90	3.20	3.90

a. Multiple modes exist. The smallest value is shown

Figure 42 IRI Histograms for *Profile*, *Thirds*, and *Sections* samples

In the same context, Table 19 shows that BBI values range from 0.02 to 0.68, where the mean values are about 0.18 and the standard deviation is between 0.07 and 0.09. In general, skewness and kurtosis values indicate that the data distribution is skewed right and that there are excess of kurtosis. Figure 43 shows the histograms for the BBI values and allow visualizing the data distribution. As in IRI data, BBI data also seems not to follow a normal distribution.

Table 19 Descriptive statistics of BBI by *Profile*, *Thirds*, and *Sections* samples

Statistics	BBI Profile	BBI Thirds	BBI Section
n	20	60	570
Mean	0.1804	0.1810	0.1759
Std. Error of Mean	0.0161	0.0107	0.0039
Median	0.1865	0.1673	0.1654
Mode	0.0195 ^a	0.1673	0.0888 ^a
Std. Deviation	0.0718	0.0830	0.0925
Variance	0.0050	0.0070	0.0090
Skewness	-0.2380	0.7660	1.4610
Std. Error of Skewness	0.5120	0.3090	0.1020
Kurtosis	-0.2100	1.4400	4.5420
Std. Error of Kurtosis	0.9920	0.6080	0.2040
Range	0.2715	0.4169	0.6716
Minimum	0.0195	0.0155	0.0107
Maximum	0.2910	0.4324	0.6823

Figure 43 BBI Histograms for *Profile*, *Thirds*, and *Sections* samples

Facing this situation, tests of normality were conducted for IRI and BBI indices in order to verify the data distribution in terms of significance level. Table 20 shows the results of these tests. From the table, it can be observed that only IRI and BBI Sections samples resulted in non-normal data (p -value <0.05). Once statistical comparisons were conducted using Sections samples, there was a need to improve normality. Thus, IRI and BBI data by the Square Root transform.

Table 20 Tests of normality for IRI and BBI for *Profile*, *Thirds*, and *Sections* samples

Sample	Sig.
IRI Profile ^b	0.20
IRI Thirds ^b	0.17
IRI Sections ^a	<0.01
BBI Profile ^b	0.20
BBI Thirds ^b	0.20
BBI Sections ^a	<0.01

a. Saphiro-Wilk test ($n \geq 100$)
b. Kolmogorov-Smirnov test ($n < 100$)

4.1.2 Correlations

A Pearson product-moment correlation coefficient was computed to assess the relationship between IRI and BBI for *Profile*, *Thirds*, and *Sections* samples. As shown in Table 21, results indicate strong and positive correlation between the variables. For the *Profile* samples, $r=0.80$, $n=20$, $p<0.001$. For the *Thirds* samples, $r=0.75$, $n=60$, $p<0.001$. For the *Sections* samples $r=0.68$, $n=570$, $p<0.001$.

Table 21 Pearson correlations between IRI and BBI for *Profile*, *Thirds*, and *Sections* samples

Correlation	BBI Profile	BBI Thirds	BBI Sections
IRI Profile	0.80	-	-
IRI Thirds	-	0.75	-
IRI Sections	-	-	0.68
Note: All values were significant (p-value < 0.001)			

Figures 44, 45, and 46 are scatter plots that summarizes the results between IRI and BBI for *Profile*, *Thirds*, and *Sections* samples, respectively. Scatter plots are presented for a visual check of the relationship between the indices, as well as to verify (empirically) the relationship between them to perform the best regression model. Overall, there was a strong, positive correlation between IRI and BBI indices. Increases in IRI were correlated with increases of BBI.

As can be seen in the figures, all samples have non-linear, positive, and strong relationship with an R-squared value ranging from 0.72 to 0.80. Although *Profile* values have the highest R-squared value, all samples are closely related. However, as the sample values number increase the dispersion increases. Figure 46 shows that the variation in *BBI Section* values ranges from about 0.10 to more than 0.40 for each IRI value.

Furthermore, the equations of the tendency lines indicate that BBI values are approximately 0.10 times the IRI values. This means that for a BBI value to reach or exceed the acceptable zone ($BBI \geq 1$) the IRI value would have to be approximately 10 m/km. It is clear that IRI values higher than 5 m/km do not represent the reality of most runways and therefore this may be a sign that point out the necessity to evaluate and adjust the scale of the BBI index.

Profile

Figure 44 IRI vs BBI for *Profile* sample

Thirds

Figure 45 IRI vs BBI for *Thirds* sample

Sections

Figure 46 IRI vs BBI for *Sections* sample

4.1.3 RMS and MAX values

Additional analysis of BBI index in terms of IRI was conducted based on the Root Mean Square (RMS) and Maximum (MAX) or peak values. As mentioned before, RMS values are a kind of arithmetic mean that takes into account the standard deviation of the sample. Figure 47 and 48 shows the RMS and MAX values of BBI but just for *Thirds* and *Sections* samples. *Profile* samples were not considered in this analysis because of the restricted size of the sample (n=20) that prevents to calculate the RMS and MAX values.

Thirds

Figure 47 RMS and MAX values for IRI and BBI *Thirds* samples

Sections

Figure 48 RMS and MAX values for IRI and BBI *Sections* samples

As expected, all samples have non-linear and positive relationship and it is important to note that MAX values show relatively strong relationship characterized by R-squared values of 0.70 for the *Sections* sample and 0.72 for the *Thirds* sample.

Similarly, RMS values correlated better than MAX values showing strong relationship with R-squared values of 0.78 for the *Thirids* sample and 0.86 for the *Sections* sample. At this stage, RMS values of BBI index for *Sections* sample shows stronger relationship.

Besides that, it can be observed that the prediction of BBI index based on RMS values for *Thirids* and *Sections* does not change significantly and are approximately 0.11 times the IRI values. However, MAX values shown high dispersion and consequently the prediction of BBI index are different for *Thirids* samples (about 0.12 times IRI) and *Sections* samples (0.17 times IRI). Figure 49 shows the Standard Deviation between BBI RMS and MAX values in terms of IRI. Deviations seem relatively small ranging from 0 to 0.15 and average of 0.05.

Figure 49 Standard Deviation between BBI RMS and MAX values in terms of IRI

In order to assess the relationships above, a Pearson correlation was calculated for IRI and BBI *Thirids* and *Sections* samples by RMS and MAX values. As shown in Table 22, correlations results indicate positive and strong correlation between the variables. RMS values for both *Thirids* samples ($r=0.86$, $n=60$, $p<0.001$) and *Sections* samples ($r=0.86$, $n=570$, $p<0.001$) has stronger relationship than MAX values.

Table 22 Pearson correlations for RMS and MAX values of IRI and BBI *Thirids* and *Sections* samples

Correlation	BBI <i>Thirids</i> RMS	BBI <i>Thirids</i> MAX	BBI <i>Sections</i> RMS	BBI <i>Sections</i> MAX
IRI <i>Thirids</i>	0.86	0.79	-	-
IRI <i>Sections</i>	-	-	0.86	0.65

Note: All values were significant (p-value < 0.001)

4.1.4 Regression Analysis for IRI vs. BBI

Table 23 presents the results of the regression analysis between IRI as independent variable and BBI as dependent variable. All three models were significant ($P\text{-value} < 0.05$) and indicate very strong and positive correlation.

Dependent Variable	Independent Variable	Coefficient	Sig.	R^2	Adjusted R^2
BBI Profile	IRI Profile	0.1036	5.4318E-13	0.94	0.89
BBI Thirds	IRI Thirds	0.1042	4.8821E-33	0.91	0.90
BBI Sections	IRI Sections	0.1008	4.9439E-258	0.87	0.87

As can be seen, regression analyses confirm that BBI index is approximately 10% of IRI index. This means that for a BBI value to reach or exceed the acceptable zone ($BBI \geq 1$) the IRI value would have to be greater than 10.0 m/km. Evidently, BBI index values are very small and all of them fall into the Acceptable region of the BBI index ($BBI < 1.0$). Small BBI values can occur due to the mathematical model process itself when the index is calculated. It is probably that the imaginary straight length used by the Boeing method is too short to comprise many bump length and bump height configurations.

In order to investigate in detail the relationship between airport pavement roughness indices and aircraft dynamic responses, the successive statistical analyses in this research were conducted using only the *Sections* sample. Also, a confidence interval based on RMS and MAX values was established to describe the data properly.

4.2 AIRCRAFT DYNAMIC RESPONSES

Aircraft dynamic response data (vertical accelerations – VACP and VACG – and dynamic loads – NGPL, MGPL, and RGPL) are the five outputs resulting from simulations performed in ProFAA. 570 pavement sections of 100 m in length were used to perform the aircraft simulations. Consequently, if the simulations involves 4 representative aircraft traversing each pavement section at 10 constant speeds from 20 to 200 knots (37 to 370 km/h), then the n is equal to 22,800 for each aircraft dynamic response variable, except for RGPL which has $n=5700$. It is because the RGPL response is simulated only for the aircraft class IV, represented by a B-747

aircraft that has their principal landing gear composed by a main landing gear and a rear landing gear.

4.2.1 Vertical Accelerations

4.2.1.1 Statistics

Table 24 provides a summary of the descriptive statistics for VACP and VACG. As can be seen, VACP and VACG values ranges from 0.0 to about 1.3g (approximately 12.8 m/s²), the average accelerations are about 0.10 and 0.05 g with standard deviation equal to 0.07 and 0.04, respectively. In general, skewness and kurtosis values are significant and clearly indicate that data are not normal. Skewness show moderate lack of symmetry with data skewed right and Kurtosis values indicate that the data distribution is heavy tailed. General VACP and VACG histograms are presented in Figure 50 in order to verify the symmetry and the distribution of the data.

Table 24 Descriptive statistics of VACP and VACG

Statistics	VACP	VACG
n	22800	22800
Mean	0.0973	0.0487
Std. Error of Mean	0.0005	0.0003
Median	0.0853	0.0417
Mode	0.0813	0.0446
Std. Deviation	0.0691	0.0443
Variance	0.0050	0.0020
Skewness	3.1900	7.8560
Std. Error of Skewness	0.0160	0.0160
Kurtosis	25.4300	122.3950
Std. Error of Kurtosis	0.0320	0.0320
Range	1.3086	1.1849
Minimum	0.0000	0.0000
Maximum	1.3086	1.1849

Figure 50 VACP and VACG Histograms

As shown in Figure 50, most of the VACP frequencies are between 0 and 0.25g while most of the VACG frequencies range from 0 to 0.2g. It means that there are few vertical accelerations values higher than 0.40 g in the sample. Tables 25 and 26 are presented in order to provide more information about vertical accelerations samples. The tables show a descriptive statistics for VACP and VACG by aircraft class, respectively.

Table 25 Descriptive statistics of VACP by aircraft class

Statistics	Class I	Class II	Class III	Class IV
n	5700	5700	5700	5700
Mean	0.1101	0.0898	0.1112	0.0782
Std. Error of Mean	0.0009	0.0009	0.0010	0.0007
Median	0.1033	0.0799	0.0930	0.0670
Mode	0.0738	0.0759	0.0616	0.0497
Std. Deviation	0.0686	0.0680	0.0783	0.0536
Variance	0.0050	0.0050	0.0060	0.0030
Skewness	4.3140	4.7620	1.7400	2.1030
Std. Error of Skewness	0.0320	0.0320	0.0320	0.0320
Kurtosis	43.3520	49.1920	4.6940	8.6640
Std. Error of Kurtosis	0.0650	0.0650	0.0650	0.0650
Range	1.2061	1.3057	0.6620	0.5683
Minimum	0.0000	0.0029	0.0033	0.0027
Maximum	1.2061	1.3086	0.6653	0.5710

Table 26 Descriptive statistics of VACG by aircraft class

Statistics	Class I	Class II	Class III	Class IV
n	5700	5700	5700	5700
Mean	0.0506	0.0464	0.0560	0.0418
Std. Error of Mean	0.0007	0.0007	0.0005	0.0004
Median	0.0458	0.0382	0.0464	0.0361
Mode	0.0446	0.0301	0.0261	0.0214
Std. Deviation	0.0513	0.0505	0.0414	0.0294
Variance	0.0030	0.0030	0.0020	0.0010
Skewness	10.2900	8.7480	1.9120	2.7920
Std. Error of Skewness	0.0320	0.0320	0.0320	0.0320
Kurtosis	148.7240	126.4380	6.1240	18.7390
Std. Error of Kurtosis	0.0650	0.0650	0.0650	0.0650
Range	1.1381	1.1836	0.3991	0.4166
Minimum	0.0000	0.0013	0.0015	0.0015
Maximum	1.1381	1.1849	0.4006	0.4181

For all the aircraft classes, VACP mean ranges from 0.08 to 0.11 g and standard deviations results less than 0.08 g. However, it can be observed that maximum VACP values decreases as aircraft class (weight) increases (except for Class III). Maximum vertical accelerations at the cockpit of Class I (1.21 g) – which represents the lightest aircraft – are more than twice of Class IV (0.57g) – the heaviest aircraft. Similarly, maximum VACP in Class II (1.31 g) are approximately twice than maximum accelerations in Class III (0.67 g).

On the other hand, Table 26 indicates that VACG mean does not vary significantly and is about 0.05g for all the aircraft classes. Similarly to cockpit accelerations, it can be observed that maximum VACG values decreases as aircraft class (weight) increases. However, maximum vertical accelerations at the center of gravity of Class I (1.14g) are almost three times of Class IV (0.42g). In the same way, maximum VACG in Class II (1.18g) are about triple than in Class III (0.40 g).

Vertical accelerations distribution can be visualized in Figure 51, which plots VACP and VACG as a function of IRI. IRI values 3.5, 3.8, and 4.0 m/km are missing values. The red dashed line indicates the limit of acceptable accelerations (0.40 g).

Figure 51 Vertical accelerations distribution based on IRI for *Sections* sample

It is evident that most of the VACP values are higher than VACG values, as indicated by the descriptive statistics. However, it can be observed that excessive accelerations at the cockpit and at the center of gravity occurred principally between 1.6 and 2.5 m/km (Regular and Poor ranges in the IRI classification). Therefore, it is extremely important that, in a network level, the evaluation of the pavement profile is based both on vertical accelerations and IRI, because of the advantage to identifying quickly critical sections that can be then addressed to the project level to establishing the M&R activities.

The number of values higher than 0.40 g is presented in Table 27 by aircraft class. There are 125 VACP values in the database that exceed this limit and occur principally in the Classes I, II, and III. The number of VACG values higher than 0.40 g (52) is about 40% less than VACP and most of them occurred in the Classes I and II.

It can be observed that values above 0.40 g represent less than 1% of the total values in each acceleration variable (n=22800). From the distribution of these values, it is evident that the aircraft cockpit is more sensible to excessive vertical accelerations than the center of gravity.

Table 27 Number of VACP and VACG values higher than 0.40 g

Aircraft	VACP	VACG
Class I	33	29
Class II	33	21
Class III	50	1
Class IV	9	1
Total	125	52

In order to verify the data distribution, a test of normality was also conducted. Table 28 shows the results of the test of normality for VACP and VACG.

Table 28 Tests of normality for VACP and VACG

Variable ^a	Sig.
VACP	< 0.01
VACG	< 0.01
a. Saphiro-Wilk test (n ≥ 100)	

As can be seen, both of vertical acceleration variables are not significant (P-value <0.05) and it means that the distribution of the data is not normal. In order to improve normality, the two variables were transformed by the Square Root Transformation. Correlation and regression analyses were then carried out considering the transformed variables.

4.2.1.2 Correlations

Table 29 presents the Pearson correlation between VACP and VACG for the *Sections* sample. Results indicate positive and strong and moderate correlation between the variables. All of them were significant, $r=0.91$, $n=22800$, $p<0.001$.

Table 29 Pearson correlation between VACP and VACG by aircraft class

		Class I		Class II		Class III		Class IV	
		VACP	VACG	VACP	VACG	VACP	VACG	VACP	VACG
Class I	VACP	1							
	VACG	0.89	1						
Class II	VACP	0.88	0.82	1					
	VACG	0.85	0.90	0.93	1				
Class III	VACP	0.65	0.46	0.79	0.65	1			
	VACG	0.65	0.47	0.76	0.66	0.95	1		
Class IV	VACP	0.65	0.48	0.79	0.64	0.90	0.86	1	
	VACG	0.68	0.53	0.78	0.68	0.87	0.89	0.94	1

As can be seen, the stronger correlations are in aircraft Classes I vs. II, as well as in Classes III vs. IV. Correlations in Class I vs. Class III and IV show moderate correlation. However, Class II vs. Class III and IV shows both strong and moderate correlation for VACP and VACG, respectively.

4.2.1.3 Regression Analysis for VACP vs. VACG

Table 30 presents results of the regression analysis between VACP which was considered as independent variable and VACG, as dependent variable. All the models were significant (P-value < 0.05) and indicate extremely strong and positive correlation. In general, vertical accelerations at the cockpit result 49% higher than vertical accelerations at the center of gravity.

Table 30 VACP vs. VACG regression analysis for *Sections* sample

Dependent Variable	Independent Variable	Coefficient	Sig.	R ²	Adjusted R ²
VACG	VACP	0.49	< 0.01	0.99	0.99
VACG Class I	VACP Class I	0.45	< 0.01	0.99	0.98
VACG Class II	VACP Class II	0.51	< 0.01	0.99	0.99
VACG Class III	VACP Class III	0.50	< 0.01	0.99	0.99
VACG Class IV	VACP Class IV	0.53	< 0.01	0.99	0.99

Furthermore, the table shows that the coefficient of Class II (0.51) is about 13% higher than Class I (0.45). Similarly, the coefficient of Class IV (0.53) is approximately 18% higher than Class I, and just 6% higher than Class III (0.50). The Class II coefficient results just 2% higher than the Class III.

Once vertical accelerations at the cockpit are about twice than accelerations at the center of gravity and consequently are considered critical, it is suggested that data analysis for future studies focus on the aircraft cockpit behavior.

4.2.2 Pavement Loads ratios

4.2.2.1 Statistics

Table 31 provides a summary of the descriptive statistics for NGPL, MGPL, and RGPL. As mentioned before, pavement load values are expressed in terms of the static ratio. The static ratio was determined by the relation between dynamic gear pavement loads (obtained through ProFAA simulations) and maximum static

pavement loads (based on official airplane characteristics for airport planning) for a certain representative aircraft type.

Table 31 Descriptive statistics of NGPL, MGPL, and RGPL

Statistics	NGPL	MGPL	RGPL
n	22800	22800	5700
Mean	0.5765	0.4725	0.4848
Std. Error of Mean	0.0010	0.0002	0.0001
Median	0.6022	0.4754	0.4846
Mode	0.0000	0.4680	0.4845
Std. Deviation	0.1444	0.0271	0.0066
Variance	0.0210	0.0010	0.0000
Skewness	-0.1210	-0.6490	2.0050
Std. Error of Skewness	0.0160	0.0160	0.0320
Kurtosis	-0.5950	5.9290	52.4960
Std. Error of Kurtosis	0.0320	0.0320	0.0650
Range	1.4551	0.5575	0.2086
Minimum	0.0000	0.0000	0.4014
Maximum	1.4551	0.5575	0.6100

a. Multiple modes exist. The smallest value is shown

Figure 52 NGPL, MGPL, and RPGL histograms

As can be seen in the table, NGPL values ranges from 0.0 to about 1.5 with mean about 0.6. It means that many dynamic loads are half than static loads. However, some dynamic loads result up to 50% higher than static loads. Static ratio values can result lower than 1.0 because of the effect of aircraft bouncing up and down when encounters an specific bump configuration (a certain length and height). As mentioned in before in the literature review, when the aircraft bounces up there is less weight on the wheels, therefore resulting in less drag load from the braking action, resulting in dynamic loads lower than static loads.

In sequence, MGPL ranges from 0.0 to 0.6 while RGPL ranges from 0.4 to 0.6, both of them with mean about 0.5. NGPL standard deviations result higher than MGPL and RGPL. In general, skewness and kurtosis values are significant and clearly indicate that data are not normal. For NGPL and MGPL, skewness shows

moderate lack of symmetry with data skewed left. RGPL data is skewed right. From a point of view of kurtosis, just MGPL approximates of a standard normal distribution, but large peaks are evident. General NGPL, MGPL, and RGPL histograms are presented in Figure 52 in order to verify the symmetry and the distribution of the data. In the same context of data distribution, Table 32 and 33 shows descriptive statistics of the pavement loads variables discretized by aircraft class. Observe in Table 32 that maximum NGPL occurs in Class II (1.46) and III (1.40). However, the mean increases as aircraft weight increases, except in Class IV probably due to the influence of their rear landing gear.

Table 32 Descriptive statistics of NGPL by aircraft class

Statistics	Class I	Class II	Class III	Class IV
n	5700	5700	5700	5700
Mean	0.3699	0.5478	0.7506	0.6377
Std. Error of Mean	0.0003	0.0004	0.0007	0.0004
Median	0.3656	0.5425	0.7350	0.6321
Mode	0.3632	0.5411	0.7281	0.6311
Std. Deviation	0.0252	0.0309	0.0563	0.0333
Variance	0.0010	0.0010	0.0030	0.0010
Skewness	2.4950	7.4240	1.4800	-0.9590
Std. Error of Skewness	0.0320	0.0320	0.0320	0.0320
Kurtosis	67.1680	193.2800	23.1800	55.8950
Std. Error of Kurtosis	0.0650	0.0650	0.0650	0.0650
Range	0.7739	1.3470	1.2073	0.8884
Minimum	0.0000	0.1081	0.1841	0.1275
Maximum	0.7739	1.4551	1.3914	1.0159

With respect to MGPL and RGPL shown in Table 33, note that mean and mode does not vary significantly and are about 0.5. Although aircraft classes III and IV have the higher minimum MGPL and RGPL ratios about 0.4, maximum loads ratios does not vary significantly and are between 0.5 and 0.6.

Table 33 Descriptive statistics of MGPL and RGPL by aircraft class

Statistics	Class I	Class II	Class III	Class IV	Class IV (RGPL)
n	5700	5700	5700	5700	5700
Mean	0.5069	0.4343	0.4685	0.4803	0.4848
Std. Error of Mean	0.0002	0.0001	0.0001	0.0001	0.0001
Median	0.5067	0.4342	0.4681	0.4804	0.4846
Mode	0.5064	0.4340	0.4679	0.4801	0.4847
Std. Deviation	0.0114	0.0063	0.0053	0.0038	0.0066
Variance	0.0000	0.0000	0.0000	0.0000	0.0000
Skewness	-28.5850	-16.6690	1.2370	-1.2340	2.0030
Std. Error of Skewness	0.0320	0.0320	0.0320	0.0320	0.0320
Kurtosis	1120.6120	562.0790	26.0670	29.9980	52.4740
Std. Error of Kurtosis	0.0650	0.0650	0.0650	0.0650	0.0650
Range	0.5575	0.2942	0.1252	0.1023	0.2086
Minimum	0.0000	0.1955	0.4160	0.4196	0.4014
Maximum	0.5575	0.4897	0.5412	0.5219	0.6100

Pavement load ratios can be visualized through Figure 53, which plots NGPL, MGPL, and RGPL as a function of IRI. Note that higher ratios also occur principally between 1.8 and 2.6 m/km and from 3.2 m/km, which corresponds to the Regular, Poor, and Very Poor ranges in the IRI classification.

Figure 53 Distribution of pavement load ratios based on IRI for Sections sample

In general, pavement loads in the main and rear gears result to be lower and more stable than pavement loads in the nose gear. Nevertheless, the results of the test of normality shown in Table 34 confirm the non-normality of the data. Therefore, these variables also were transformed using the Square Root Transformation. Correlation and regression analyses were carried out considering the transformed variables.

Table 34 Tests of normality for NGPL, MGPL, and RGPL

Variable ^a	Sig.
NGPL	< 0.01
MGPL	< 0.01
RGPL	< 0.01

a. Saphiro-Wilk test ($n \geq 100$)

4.2.2.2 Correlations

Table 35 presents the Pearson correlation between NGPL, MGPL, and RGPL for the *Sections* sample and by aircraft class. All of them were significant ($p < 0.001$).

Table 35 Pearson correlation for NGPL, MGPL, and RGPL by aircraft class

		Class I		Class II		Class III		Class IV		
		NGPL	MGPL	NGPL	MGPL	NGPL	MGPL	NGPL	MGPL	RGPL
Class I	NGPL	1								
	MGPL	0.25	1							
Class II	NGPL	0.49	0.27	1						
	MGPL	0.15	0.94	0.13	1					
Class III	NGPL	0.52	0.31	0.66	0.23	1				
	MGPL	-0.09	0.39	-0.03	0.59	-0.1	1			
Class IV	NGPL	0.52	0.45	0.65	0.33	0.72	0.01	1		
	MGPL	-0.18	0.39	-0.09	0.58	-0.09	0.74	-0.12	1	
	RGPL	-0.10	0.36	-0.08	0.57	0.05	0.8	-0.14	0.81	1

As can be seen from the table, the results indicate very strong and positive correlation between the following variables:

- MGPL Class I vs. MGPL Class II ($r = 0.94$)
- MGPL Class IV vs. RGPL Class IV (0.81)
- MGPL Class III vs. RGPL Class IV (0.80)
- MGPL Class III vs. MGPL Class IV (0.74)
- NGPL Class IV vs. NGPL Class III (0.72)

Observe how pavement loads correlations are high for two visible groups. The first group formed by classes I and II has strong correlation between their MGPL. The second group formed by classes III and IV has strong correlation not only for MGPL but also for NGPL and RGPL. This is a curious fact that could allow conducting further studies based, specifically, on two aircraft classes: light and heavy.

Still in Table 35, results indicate moderate and positive correlation between the following variables:

- NGPL Class II vs. NGPL Class III (0.66)
- NGPL Class II vs. MGPL Class IV (0.65)
- MGPL Class II vs. MGPL Class III (0.59)
- MGPL Class II vs. MGPL Class IV (0.58)
- MGPL Class II vs. RGPL Class IV (0.57)
- NGPL Class I vs. NGPL Class III (0.52)
- NGPL Class I vs. NGPL Class IV (0.52)
- NGPL Class I vs. NGPL Class II (0.49)
- MGPL Class I vs. NGPL Class IV (0.45)

In general, pavement loads in Class II has moderate and positive correlation ($r = 0.57$ to 0.66) with Classes III and IV. Similarly, there are moderate and positive correlation between Class I and Classes II, III, and IV ($r = 0.45$ to 0.52).

It was observed weak and positive correlations for the variables listed below:

- MGPL Class I vs. MGPL Class III (0.39)
- MGPL Class I vs. MGPL Class IV (0.39)
- MGPL Class I vs. RGPL Class IV (0.36)
- MGPL Class II vs. NGPL Class IV (0.33)
- MGPL Class I vs. NGPL Class III (0.31)
- MGPL Class I vs. NGPL Class II (0.27)
- MGPL Class I vs. NGPL Class I (0.25)
- MGPL Class II vs. NGPL Class III (0.23)
- MGPL Class II vs. NGPL Class I (0.15)
- MGPL Class II vs. NGPL Class II (0.13)

As shown in the list, MGPL in Class I has weak correlation with NGPL in Classes I, II, and III ($r = 0.25$ to 0.31), as well as with MGPL and RGPL in Classes III and IV ($r = 0.36$ to 0.39). In general, pavement loads at the nose landing gear weakly correlated with pavement loads at the main landing gear, except between classes III and IV where there are strong correlation ($r = 0.72$).

4.2.2.3 Regression Analysis for NGPL vs. MGPL and RGPL

Table 36 presents results of the regression analysis between NGPL (independent variable) and MGPL and RGPL (dependent variables). All the models were significant ($P\text{-value} < 0.05$) and indicate perfect and positive correlation. In general, most of pavement load ratios in the main gear are 80% of those in the nose gear.

Table 36 NGPL vs. MGPL and RGPL regression analysis for *Sections* sample

Dependent Variable	Independent Variable	Coefficient	Sig.	R ²	Adjusted R ²
MGPL	NGPL	0.80	< 0.01	0.98	0.98
MGPL Class I	NGPL Class I	1.37	< 0.01	1.00	1.00
MGPL Class II	NGPL Class II	0.79	< 0.01	1.00	1.00
MGPL Class III	NGPL Class III	0.79	< 0.01	1.00	1.00
MGPL Class IV	NGPL Class IV	0.87	< 0.01	1.00	1.00
RGPL Class IV	NGPL Class IV	0.87	< 0.01	1.00	1.00
RGPL Class IV	MGPL Class IV	0.99	< 0.01	1.00	1.00

However, it can be observed that for the Class I, pavement load ratios in the main gear result 137% higher than in the nose gear. On the other hand, pavement loads in main and rear gears of aircraft Class IV can be assumed equal.

4.2.3 Vertical Accelerations vs. Speed

Before to compare aircraft dynamic responses with pavement roughness indices it is extremely important to know the behavior of the vertical accelerations and pavement loads from an operational speed point of view. As mentioned previously, aircraft simulations in this research involved ten constant speeds, from 20 to 200 knots (37 to 370 km/h). In order to facilitate the data analyses the speeds were discretized into five categories: Very Low (20 and 40 knots – 37 and 74 km/h), Low (60 and 80 knots – 111 and 148 km/h), Medium (100 and 120 knots – 185 and 222 km/h), High (140 and 160 knots – 259 and 296 km/h), and Very High (180 and 200 knots – 333 and 370 km/h).

Figure 54 plots maximum vertical acceleration versus speed involving all aircraft classes. As expected, accelerations increase as speed increases and VACP are higher than VACG. However, it can be observed that from 40 to 120 knots VACP is about twice or more higher than VACG. From 140 knots VACP and VACG tend to be approximately equal, with little variations about 10%. Additionally, it can be seen that VACP and VACG reach the critical limit of 0.40 g at 80 knots (Low speed) and 140 knots (High speed), respectively. It means that critical accelerations in the cockpit may occur while the aircraft is in Low or High operational speeds.

Figure 54 Vertical accelerations by Speed in knots

Figures 55 to 58 show vertical accelerations versus speed by aircraft class.

Aircraft Class I

Figure 55 Vertical accelerations vs. speed for the aircraft class I

Figure 55 shows that from 20 to 60 knots vertical accelerations at the cockpit and center of gravity have not substantial dispersion. However, as speed increases acceleration increases and becomes to be more dispersed. Note that VACP and VACG in aircraft class I exceed critical accelerations at 140 knots.

As can be seen in Figure 56, dispersion of accelerations in aircraft class II are noticeable from 40 knots onwards. In this class, vertical accelerations in the cockpit become to be high from 80 knots but only exceed 0.40 g at 140 knots. VACG exceeds critical acceleration limit at 160 knots.

Aircraft Class II

Figure 56 Vertical accelerations vs. speed for the aircraft class II

Aircraft Class III

Figure 57 Vertical accelerations vs. speed for the aircraft class III

As shown in Figure 57, vertical accelerations in aircraft class III exceeding 0.40 g are lower than those in classes I and II. However, aircraft class III presents high rate of dispersion from 60 knots in both cockpit and center of gravity. VACP reach and exceed 0.40 g at 80 and 120 knots, respectively.

Aircraft Class IV

Figure 58 Vertical accelerations vs. speed for the aircraft class IV

Figure 58 shows that from 80 knots vertical accelerations at the cockpit and center of gravity of aircraft class IV have moderate dispersion. As speed increases acceleration increases and also becomes to be more dispersed. However, VACP and VACG exceed critical accelerations only at 160 and 200 knots, respectively. It is

evident that vertical accelerations increase as operational speed increases and they decrease as aircraft weight increases. In the case of aircraft class I, cockpit and center of gravity accelerations exceed 0.40 g from 140 knots.

The same occurs in aircraft class II but VACG exceed the critical limit just at 160 knots. In contrast, VACP accelerations in class III exceed 0.40 g when the aircraft speed is 120 knots, however, accelerations at the center of gravity were lower than 0.40 g in all speeds. Similarly, cockpit and center of gravity accelerations in aircraft class IV (heaviest aircraft) only exceed the critical limit at 160 and 200 knots, respectively.

4.2.4 Pavement Load ratios vs. Speed

Figure 59 plots maximum pavement load ratios versus speed involving all aircraft classes. It can be observed that NGPL ratios increase as speed increases and result in more than twice higher than MGPL and RGPL. Also, it is note that MGPL ratios are just about 3% higher than RGPL ratios when the speeds are between 20 and 120 knots. However, from 140 knots, MGPL are about 5% lower than RGPL. In general, NGPL ratios vary at a higher rate than MGPL and RGPL ratios that have a relatively constant behavior along the speeds with an average ratio of 0.50 as speed increases.

Figure 59 Pavement load ratios by Speed in knots

Figures 60 to 63 show pavement load ratios versus speed by aircraft class in order to visualize in detail the data dispersion behavior for each constant speed.

Figure 60 Pavement load ratios by speed for the aircraft class I

As can be seen in Figure 60, NGPL ratios in class I aircraft are lower than MGPL ratios. This aircraft class was the only one with pavement load ratios in the main gear higher than in the nose gear. However, NGPL ratios vary at a higher rate than MGPL. The figure also shows that NGPL and MGPL ratios become relatively constant up to 140 and 80 knots, respectively. Note in Figure 61 that the dispersion of NGPL in class II are higher than those in class I.

Figure 61 Pavement load ratios by speed for the aircraft class II

Figure 62 Pavement load ratios by speed for the aircraft class III

As shown in Figure 62, NGPL in class III are even higher than those in class I and II. Apparently, the high rate of dispersion of pavement load ratios in aircraft class III indicates high sensitivity to pavement roughness. In addition, it can be observed that this aircraft class presents the biggest difference between NGPL and MGPL (about 0.30).

Figure 63 Pavement load ratios by speed for the aircraft class IV

In general, it was perceived that vertical accelerations and pavement load ratios become to be critical as the operational speed increases and as the aircraft weight decreases. In other words, light-weight aircraft may have more risk to reach critical vertical accelerations in the cockpit, principally when operates above 120 knots. However, certain aircraft classified into class III also may experience critical cockpit accelerations from 80 knots.

On the other hand, pavement load ratios appear to be more stable or relatively constant as speed increases. Also, once the ratios are directly related to the maximum static loads and consequently to the aircraft weight, it is possible to establish average MGPL and RGPL values by aircraft class valid for all operational speeds. However, regression analyses discussed later will help to predict each one of the variables, including vertical accelerations and NGPL ratios.

4.2.5 Vertical Accelerations vs. IRI

The following figures and tables aim to present aircraft dynamic responses as a function of IRI, once it is the principal independent variable and the starting point in this study to perform all the statistical analyses. Pearson correlations as well as regression analyses are also presented.

Figures 64 to 68 show maximum vertical accelerations versus IRI by aircraft class at each speed range. As a complement and with the intention to compare maximum accelerations with the average, Tables 37 to 41 also presents the RMS values.

Figure 64 and Table 37 indicates, for Very Low speed, that vertical accelerations increase as pavement roughness increases. In this context, maximum values vary at a rate of about 20% in VACP and 30% in VACG as the IRI increases. Similarly, RMS values vary at a rate of about 50% both for VACP and VACG as the IRI increases. In general, it can be observed that at Very Low speed the irregularities in the pavement profiles did not generate accelerations above 0.4 g.

Very Low speed (20 - 40 knots)

Figure 64 Maximum vertical accelerations vs. IRI by aircraft class at the “Very Low” speed

Table 37 RMS vertical accelerations vs. IRI by aircraft class at the “Very Low” speed

IRI Range	VACP				VACG			
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
Very Good	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01
Good	0.05	0.04	0.04	0.03	0.02	0.02	0.02	0.02
Regular	0.07	0.05	0.05	0.03	0.03	0.02	0.02	0.02
Poor	0.08	0.06	0.06	0.04	0.04	0.03	0.03	0.02
Very Poor	0.10	0.08	0.09	0.05	0.05	0.04	0.04	0.03

However, once the speed increases to 60 and 80 knots pavement roughness with IRI above 2.5 m/km become to be a problem for the aircraft class III which reaches the critical limit. Figure 65 indicates that maximum values vary at a rate of about 30% in VACP and 20% in VACG. Correspondingly, Table 38 shows that RMS values vary at a rate of about 40% both for VACP and VACG. In general, at this speed pavement roughness does not contribute to excessive vertical accelerations.

Figure 65 Maximum vertical accelerations vs. IRI by aircraft class at the “Low” speed

Table 38 RMS vertical accelerations vs. IRI by aircraft class at the “Low” speed								
IRI Range	VACP (g)				VACG (g)			
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
Very Good	0.04	0.04	0.05	0.04	0.02	0.02	0.02	0.02
Good	0.08	0.07	0.09	0.06	0.04	0.03	0.04	0.03
Regular	0.10	0.08	0.10	0.07	0.05	0.04	0.05	0.03
Poor	0.13	0.09	0.11	0.07	0.06	0.04	0.05	0.03
Very Poor	0.16	0.13	0.17	0.10	0.08	0.07	0.08	0.05

When the aircraft speed is between 100 and 120 knots vertical accelerations increase considerably, mainly in aircraft class III. At this speed, pavement roughness begins to be critical when IRI range is Regular (1.5 to 2.0 m/km). As can be seen in Figure 66, maximum values vary at a rate of about 20% in VACP and 40% in VACG. Respectively, Table 39 shows that RMS values vary at a rate of about 40% in VACP and 60% in VACG.

Figure 66 Maximum vertical accelerations vs. IRI by aircraft class at the “Medium” speed

Table 39 RMS vertical accelerations vs. IRI by aircraft class at the “Medium” speed								
IRI Range	VACP (g)				VACG (g)			
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
Very Good	0.06	0.06	0.08	0.06	0.03	0.02	0.04	0.03
Good	0.10	0.09	0.11	0.08	0.05	0.04	0.05	0.04
Regular	0.32	0.11	0.14	0.10	0.32	0.05	0.07	0.05
Poor	0.14	0.12	0.15	0.10	0.07	0.06	0.07	0.05
Very Poor	0.20	0.17	0.21	0.15	0.10	0.09	0.10	0.08

Figure 67 indicates that maximum values vary at a rate of about 30% in VACP and 70% in VACG as the IRI increases. Similarly, Table 40 shows that RMS values vary at a rate of about 30% in VACP and 40% in VACG. At 140 knots, IRI values from 1.5 m/km generate vertical accelerations that exceed 0.40 g in the four aircraft classes. Once mainly aircraft rotation speeds fall into this speed range, it is extremely important that pavement roughness begins to be monitored when the roughness is still into the Good range (1.0 to 1.5 m/km).

High speed (140 - 160 knots)

Figure 67 Maximum vertical accelerations vs. IRI by aircraft class at the “High” speed

Table 40 RMS vertical accelerations vs. IRI by aircraft class at the “High” speed

IRI Range	VACP (g)				VACG (g)			
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
Very Good	0.07	0.07	0.11	0.08	0.03	0.04	0.06	0.04
Good	0.12	0.11	0.14	0.10	0.05	0.05	0.07	0.05
Regular	0.17	0.15	0.17	0.13	0.12	0.10	0.09	0.07
Poor	0.17	0.14	0.18	0.13	0.09	0.09	0.09	0.07
Very Poor	0.25	0.20	0.25	0.18	0.13	0.12	0.13	0.10

As shown in Figure 68, speeds between 180 to 200 knots make the maximum values vary at a rate of about 60% in VACP and 90% in VACG. Respectively, Table 41 shows that RMS values vary at a rate of about 30% in VACP and 40% in VACG.

Figure 68 Maximum vertical accelerations vs. IRI by aircraft class at the “Very High” speed

Table 41 RMS vertical accelerations vs. IRI by aircraft class at the “Medium” speed								
IRI Range	VACP (g)				VACG (g)			
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV
Very Good	0.08	0.10	0.14	0.10	0.04	0.05	0.08	0.06
Good	0.13	0.12	0.16	0.11	0.05	0.06	0.09	0.06
Regular	0.22	0.22	0.20	0.14	0.18	0.18	0.11	0.08
Poor	0.23	0.21	0.22	0.16	0.16	0.15	0.13	0.09
Very Poor	0.30	0.26	0.29	0.22	0.18	0.17	0.15	0.13

Evidently, vertical accelerations above 0.40 g may be occurring due to several bump length and bump height configurations. For this reason, the evaluation of the elevation profile it is extremely important and should be included in pavement roughness assessments. In general, VACP can increase at a rate of 20 to 60% as the IRI increases. Furthermore, although vertical accelerations in the center of gravity are less than those generated in the cockpit, they can be increased at a rate of 20 to 90 % as the IRI increases.

4.2.6 Pavement Load ratios vs. IRI

Figures 69 to 73 show maximum pavement load ratios versus IRI by aircraft class at each speed range. As a compliment and with the intention to compare maximum load ratios with the average, Tables 42 to 46 also presents the RMS values. The dashed black line located in the figures serves as a reference to indicate when dynamic loads are equal to static loads.

As can be seen in Figure 69 and Table 42, pavement load ratios are relatively constant as pavement roughness increases. Note also that average ratios are about 0.60 in NGPL and 0.50 in MGPL/RGPL. It means that, at very low speeds, dynamic pavement loads in the nose, main, and rear landing gears are approximately half of the maximum static pavement load.

Very Low speed (20 - 40 knots)

Figure 69 Maximum pavement load ratios vs. IRI by aircraft class at the "Very Low" speed

Table 42 RMS pavement load ratios vs. IRI by aircraft class at the "Very Low" speed

IRI Range	NGPL				MGPL				RGPL
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV	Class IV
Very Good	0.36	0.54	0.73	0.63	0.51	0.43	0.47	0.48	0.48
Good	0.36	0.54	0.73	0.63	0.51	0.43	0.47	0.48	0.48
Regular	0.36	0.54	0.73	0.63	0.51	0.43	0.47	0.48	0.48
Poor	0.36	0.54	0.73	0.63	0.51	0.43	0.47	0.48	0.48
Very Poor	0.37	0.54	0.74	0.63	0.51	0.43	0.47	0.48	0.48

As expected, Figure 70 and Table 43 also show that load ratios are constant as pavement roughness increases. However, it was observed a small increase as the speed increased. At Low speeds, maximum NGPL in class III can reach 0.8 when the pavement roughness is between 1.5 and 2.0 m/km and also can exceed 1.0 when roughness is above 2.5 m/km. In general, when the aircraft speed is between 60 and 80 knots NGPL are approximately 40% higher than MGPL and RGPL. Additionally, it can be observed that the higher NGPL ratio corresponds to IRI Very Poor.

Low speed (60 - 80 knots)

Figure 70 Maximum pavement load ratios vs. IRI by aircraft class at the "Low" speed

Table 43 RMS pavement load ratios vs. IRI by aircraft class at the "Low" speed

IRI Range	NGPL				MGPL				RGPL
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV	Class IV
Very Good	0.36	0.54	0.73	0.63	0.51	0.43	0.47	0.48	0.48
Good	0.37	0.54	0.74	0.63	0.51	0.43	0.47	0.48	0.48
Regular	0.37	0.55	0.75	0.64	0.32	0.43	0.47	0.48	0.48
Poor	0.37	0.55	0.75	0.64	0.51	0.43	0.47	0.48	0.48
Very Poor	0.37	0.55	0.77	0.64	0.51	0.43	0.47	0.48	0.49

As shown in Figure 71, maximum NGPL in aircraft class III are equal or above the maximum static load, regardless of the pavement roughness range. In general, when the aircraft speed is between 100 and 120 knots, NGPL can be approximately 60% higher than MGPL and RGPL. At this speed the IRI range Poor has the higher NGPL ratio.

Figure 71 Maximum pavement load ratios vs. IRI by aircraft class at the “Medium” speed

Table 44 RMS pavement load ratios vs. IRI by aircraft class at the “Medium” speed									
IRI Range	NGPL				MGPL				RGPL
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV	Class IV
Very Good	0.37	0.55	0.74	0.64	0.51	0.43	0.47	0.48	0.48
Good	0.37	0.55	0.75	0.64	0.51	0.43	0.47	0.48	0.48
Regular	0.32	0.55	0.76	0.64	0.32	0.43	0.47	0.48	0.49
Poor	0.37	0.55	0.76	0.64	0.51	0.43	0.47	0.48	0.48
Very Poor	0.39	0.56	0.79	0.65	0.51	0.43	0.47	0.48	0.49

Figure 72 and Table 45 indicates that pavement load ratios at high speed are very similar than those at medium speed. However, at this speed the IRI range Regular has the higher NGPL ratio.

High speed (140 - 160 knots)

Figure 72 Maximum pavement load ratios vs. IRI by aircraft class at the "High" speed

Table 45 RMS pavement load ratios vs. IRI by aircraft class at the "High" speed

IRI Range	NGPL				MGPL				RGPL
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV	Class IV
Very Good	0.37	0.55	0.75	0.64	0.51	0.43	0.47	0.48	0.48
Good	0.37	0.55	0.76	0.64	0.51	0.43	0.47	0.48	0.48
Regular	0.37	0.55	0.77	0.64	0.51	0.44	0.47	0.48	0.49
Poor	0.38	0.55	0.76	0.64	0.51	0.43	0.47	0.48	0.49
Very Poor	0.40	0.56	0.79	0.64	0.51	0.43	0.47	0.48	0.49

Finally, when aircraft speed is between 180 and 200 knots and pavement roughness is above 2.5 m/km, NGPL in aircraft classes II, III, and IV are higher than static loads (see Fig. 73 and Table 46).

Very High speed (180 - 200 knots)

Figure 73 Maximum pavement load ratios vs. IRI by aircraft class at the “Very High” speed

Table 46 RMS pavement load ratios vs. IRI by aircraft class at the “Very High” speed

IRI Range	NGPL				MGPL				RGPL
	Class I	Class II	Class III	Class IV	Class I	Class II	Class III	Class IV	Class IV
Very Good	0.37	0.55	0.76	0.64	0.51	0.43	0.47	0.48	0.49
Good	0.37	0.55	0.76	0.64	0.51	0.43	0.47	0.48	0.48
Regular	0.38	0.55	0.77	0.65	0.51	0.44	0.47	0.48	0.49
Poor	0.39	0.57	0.78	0.65	0.51	0.43	0.47	0.48	0.49
Very Poor	0.40	0.57	0.79	0.64	0.51	0.43	0.47	0.48	0.49

Table 47 is also presented in order to summarize the information about the pavement load ratios.

Table 47 Summary of the pavement load ratios by aircraft class

Aircraft Class	NGPL	MGPL	RGPL
I	0.40 – 0.50	0.50	-
II	0.60 – 0.70	0.40 – 0.50	-
III	0.80 – 1.00	0.50	-
IV	0.60 – 0.80	0.50	0.50

4.3 STATISTICAL COMPARISONS

4.3.1 Correlations

This section is a comparison of the response data to the pavement roughness indices. As well as in previous statistics, in this chapter, Pearson's correlation was used to analyze the suitability of roughness indices (by *Sections* sample - pavement profiles divided into sections of 100 m in length) in capturing aircraft dynamic response to pavement roughness. The correlations take into account all constant speeds (20 to 200 knots) and were performed for the overall data and by aircraft class.

4.3.1.1 Vertical Accelerations vs. Pavement Roughness Indices

Table 48 provides the correlation of the pavement roughness indices, IRI and BBI, with vertical accelerations at the aircraft cockpit (VACP) and at the center of gravity (VACG). All the coefficients were significant (P-value < 0.05).

Table 48 Pearson correlation coefficients for vertical accelerations and pavement roughness indices; by overall data and aircraft class

	Overall		Class I		Class II		Class III		Class IV	
	VACP	VACG	VACP	VACG	VACP	VACG	VACP	VACG	VACP	VACG
IRI	0.52	0.50	0.65	0.57	0.54	0.52	0.50	0.49	0.44	0.45
BBI	0.60	0.56	0.62	0.58	0.64	0.59	0.62	0.57	0.58	0.55

The table shows good and positive correlations for both roughness indices. The average coefficient for IRI is 0.50 while the average coefficient for BBI is 0.60; consequently, BBI shows about 20% higher correlation than IRI. In addition, it can be observed that the lower correlation coefficients for IRI corresponds to the aircraft class IV and result approximately 10% lower than the average. Conversely, correlation coefficients for BBI remain relatively constant in all aircraft classes, varying approximately 3.5% with respect to the average. In the context of vertical accelerations, BBI shows a higher correlation than IRI.

4.3.1.2 Pavement Loads vs. Pavement Roughness Indices

Table 49 provides the correlation of the pavement roughness indices, IRI and BBI, with pavement load ratios at the nose, main, and rear landing gears (NGPL,

MGPL, and RGPL, respectively). Most of the coefficients were significant (P-value < 0.05).

Table 49 Pearson correlation coefficients for pavement load ratios and pavement roughness indices; by overall data and aircraft class

	Overall			Class I		Class II		Class III		Class IV		
	NGPL	MGPL	RGPL	NGPL	MGPL	NGPL	MGPL	NGPL	MGPL	NGPL	MGPL	RGPL
IRI	0.02	0.00	0.02	0.12	<u>-0.02</u>	0.09	<u>-0.02</u>	0.13	0.03	0.04	<u>0.00</u>	<u>0.02</u>
BBI	0.05	0.00	0.04	0.23	-0.05	0.21	0.01	0.25	0.00	0.12	-0.04	0.04

____ P-value > 0.05

As can be seen, both roughness indices have low correlation with pavement load ratios, principally with MGPL and RGPL. Even so, BBI shows higher correlation than IRI. The average coefficient for IRI is 0.04 while the average coefficient for BBI is 0.07; consequently, BBI shows about 75% higher correlation than IRI. Note also that the higher coefficients corresponds to the NGPL ratios of the aircraft classes I, II, and III. The coefficients for NGPL in aircraft class IV result approximately 36% and 52% lower than the average of the other aircraft classes, for IRI and BBI, respectively. Although the correlations are low, BBI is the pavement roughness index that best correlates with pavement load ratios.

4.3.2 Regression Analyses

Simple linear regressions were carried out to investigate the relationship between aircraft dynamic responses and pavement roughness indices. Regression models were based on *Sections* sample and performed considering all constant speeds (20 to 200 knots). The given equations are for the overall data as well as for RMS and MAX values and aircraft classes.

The models assume that the constant is zero and that both BBI and IRI are independent variables. Furthermore, once variables were transformed to improve data normality, coefficients are given in each equation in order to obtain directly the correspondent estimated value.

The last two columns in the tables relate to the IRI and BBI estimated when vertical accelerations reach 0.35 g and 0.40 g and when pavement load ratios reach 1.5 and 2.0. It allows identifying critical situations (the IRI or BBI value that reaches critical accelerations or indicates high pavement load ratios) in terms of pavement

roughness indices. These critical situations were highlighted and then inserted in a separate table as a summary.

All the models were significant ($P\text{-value} < 0.05$) and indicated very strong and positive coefficient of determination. However, the scatterplots of standardized residuals showed that only vertical acceleration data meet the assumptions of homogeneity of variance and linearity of the residuals were normally distributed (these scatterplots can be seen in Appendix G).

4.3.2.1 VACP vs. IRI & BBI

Tables 50 and 51 present the results of the regression analysis between IRI and BBI as independent variable and VACP as dependent variable, respectively.

Table 50 Linear regression analyses for VACP vs. IRI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	IRI to reach 0.35 g	IRI to reach 0.40 g
VACP Overall	IRI	$VACP = (0.1563 * IRI)^2$	0.85	3.8	4.0
VACP RMS	IRI	$VACP = (0.1425 * IRI)^2$	0.85	4.2	4.4
VACP MAX	IRI	$VACP = (0.1729 * IRI)^2$	0.78	3.4	3.7
VACP Class I	IRI	$VACP = (0.1697 * IRI)^2$	0.89	3.5	3.7
VACP Class II	IRI	$VACP = (0.1507 * IRI)^2$	0.86	3.9	4.2
VACP Class III	IRI	$VACP = (0.1664 * IRI)^2$	0.85	3.6	3.8
VACP Class IV	IRI	$VACP = (0.1385 * IRI)^2$	0.83	4.3	4.6

Table 51 Linear regression analyses for VACP vs. BBI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	BBI to reach 0.35 g	BBI to reach 0.40 g
VACP Overall	BBI	$VACP = (0.7174)^2 * BBI$	0.93	0.7	0.8
VACP RMS	BBI	$VACP = (0.7194)^2 * BBI$	0.99	0.7	0.8
VACP MAX	BBI	$VACP = (1.2970)^2 * BBI$	0.91	0.2	0.2
VACP Class I	BBI	$VACP = (0.7690)^2 * BBI$	0.94	0.6	0.7
VACP Class II	BBI	$VACP = (0.6917)^2 * BBI$	0.94	0.7	0.8
VACP Class III	BBI	$VACP = (0.7665)^2 * BBI$	0.93	0.6	0.7
VACP Class IV	BBI	$VACP = (0.6424)^2 * BBI$	0.93	0.8	1.0

Results in Table 50 shows that there is a strong positive linear relationship between VACP and IRI, which can be confirmed with the average Pearson's correlation coefficient of 0.53 (see Table 48). The critical situation occurs in the model VACP MAX which considers maximum or peak vertical accelerations at the

aircraft cockpit. It means that vertical accelerations become to be critical (0.35 g) when the IRI is 3.4 m/km and exceeds the critical limit when it is above 3.7 m/km. Furthermore, the R^2 value was 0.78 so 78% of the variation in VACP can be explained by the critical model containing only IRI.

On the other hand, results in Table 51 shows also that there is a strong positive linear relationship between VACP and BBI, which can be confirmed with the average Pearson's correlation coefficient of 0.61 (see Table 48). However, the average R^2 for BBI is 0.94, about 11% higher than IRI. In this case, the critical situation also occurs in the model VACP MAX and means that vertical accelerations exceed 0.35 g when BBI is 0.20.

Evidently, a BBI value equal or near to 0.20 is very low and falls into the Acceptable region of the BBI classification. Despising the maximum accelerations model, the average BBI to reach 0.40 g is 0.8. Figure 74 illustrates this situation with the BBI classification graph as a reference. In this context, pavement sections with BBI values that fall into the acceptable region probably are subjected to high accelerations that reach or exceed 0.40 g. Thus, from a point of view of cockpit accelerations, it is clear the necessity to evaluate and adjust the scale of the BBI index.

Figure 74 BBI to reach 0.40 g VACP in the Boeing Bump Index classification (FAA, 2009)

4.3.2.2 VACG vs. IRI & BBI

Table 52 and 53 presents the results of the regression analysis between IRI and BBI and VACG, respectively.

Similarly as VACP, results in Table 52 shows that there is a strong positive linear relationship between VACG and IRI, which can be confirmed with the average Pearson's correlation coefficient of 0.50 (see Table 48). The critical situation occurs also in the model VACG MAX which considers maximum or peak vertical accelerations at the center of gravity. In this case, vertical accelerations become to be critical (0.35 g) when IRI is 4.7 m/km and exceeds the critical limit when it is above 5.1 m/km. The R^2 value was 0.73 so 73% of the variation in VACG can be explained by the critical model containing only IRI.

Table 52 Linear regression analyses for VACG vs. IRI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	IRI to reach 0.35 g	IRI to reach 0.40 g
VACG Overall	IRI	$VACG = (0.1101 * IRI)^2$	0.84	5.4	5.7
VACG RMS	IRI	$VACG = (0.1017 * IRI)^2$	0.84	5.8	6.2
VACG MAX	IRI	$VACG = (0.1249 * IRI)^2$	0.73	4.7	5.1
VACG Class I	IRI	$VACG = (0.1137 * IRI)^2$	0.87	5.2	5.6
VACG Class II	IRI	$VACG = (0.1075 * IRI)^2$	0.84	5.5	5.9
VACG Class III	IRI	$VACG = (0.1177 * IRI)^2$	0.84	5.0	5.4
VACG Class IV	IRI	$VACG = (0.1014 * IRI)^2$	0.84	5.8	6.2

Table 53 Linear regression analyses for VACG vs. BBI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	BBI to reach 0.35 g	BBI to reach 0.40 g
VACG Overall	BBI	$VACG = (0.5038)^2 * BBI$	0.92	1.4	1.6
VACG RMS	BBI	$VACG = (0.5322)^2 * BBI$	0.97	1.2	1.4
VACG MAX	BBI	$VACG = (1.0972)^2 * BBI$	0.84	0.3	0.3
VACG Class I	BBI	$VACP = (0.5167)^2 * BBI$	0.93	1.3	1.5
VACG Class II	BBI	$VACP = (0.4902)^2 * BBI$	0.91	1.5	1.7
VACG Class III	BBI	$VACP = (0.5400)^2 * BBI$	0.92	1.2	1.4
VACG Class IV	BBI	$VACP = (0.4681)^2 * BBI$	0.92	1.6	1.8

Results in Table 53 shows also strong positive linear relationship between VACG and BBI, which can be confirmed with the average Pearson's correlation coefficient of 0.57 (see Table 48). However, the average R^2 for BBI is 0.92, about 11% higher than the average R^2 for IRI. In this case the critical situation also occurs

in the model VACG MAX, but this time accelerations exceeding 0.40 g occur when BBI is 0.30, as can be seen in Figure 75. Despising the maximum acceleration model the average BBI to reach 0.40 g is 1.6.

Again it can be seen that pavement sections with BBI values in the acceptable region probably are subjected to high accelerations that reach or exceed 0.40 g. Thus, from a point of view of center of gravity accelerations, it is also evident that the scale of the BBI index needs to be evaluated and adjusted.

Figure 75 BBI to reach 0.40 g VACG in the Boeing Bump Index classification (FAA, 2009)

4.3.2.3 NGPL vs. IRI & BBI

Table 54 and 55 presents the results of the regression analysis between IRI and BBI and NGPL, respectively.

Table 54 Linear regression analyses for NGPL vs. IRI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R ²	IRI to reach 1.5 ratio	IRI to reach 2.0 ratio
NGPL Overall	IRI	$NGPL = (0.3701 * IRI)^2$	0.81	3.3	3.8
NGPL RMS	IRI	$NGPL = (0.3000 * IRI)^2$	0.75	4.1	4.7
NGPL MAX	IRI	$NGPL = (0.3133 * IRI)^2$	0.75	3.9	4.5
NGPL Class I	IRI	$NGPL = (0.2990 * IRI)^2$	0.82	4.1	4.7
NGPL Class II	IRI	$NGPL = (0.3636 * IRI)^2$	0.82	3.4	3.9
NGPL Class III	IRI	$NGPL = (0.4259 * IRI)^2$	0.82	2.9	3.3
NGPL Class IV	IRI	$NGPL = (0.3920 * IRI)^2$	0.82	3.1	3.6

Table 55 Linear regression analyses for NGPL vs. BBI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R ²	BBI to reach 1.5 ratio	BBI to reach 2.0 ratio
NGPL Overall	BBI	$NGPL = (1.7352)^2 * BBI$	0.92	0.5	0.7
NGPL RMS	BBI	$NGPL = (1.2708)^2 * BBI$	0.91	0.9	1.2
NGPL MAX	BBI	$NGPL = (1.7071)^2 * BBI$	0.91	0.5	0.7
NGPL Class I	BBI	$NGPL = (1.4014)^2 * BBI$	0.93	0.8	1.0
NGPL Class II	BBI	$NGPL = (1.7046)^2 * BBI$	0.93	0.5	0.7
NGPL Class III	BBI	$NGPL = (1.9968)^2 * BBI$	0.93	0.4	0.5
NGPL Class IV	BBI	$NGPL = (1.8380)^2 * BBI$	0.93	0.4	0.6

Although linear regression models shown in Table 54 indicate very strong and positive coefficients of determination, correlation results in Table 49 shows that there was a low positive linear relationship between NGPL and IRI, with average Pearson's correlation coefficient of 0.08. Nevertheless, the critical situation occurs in the model NGPL Class III which considers high pavement load ratios at the nose landing gear of the aircraft class III. It means that when IRI is 2.9 m/km pavement loads by the nose gear are 50% higher than their respective static load (NGPL = 1.5). If IRI is above 3.3 m/km then pavement loads result in twice the static load (NGPL = 2.0). Furthermore, the R² value was 0.82 so 82% of the variation in NGPL can be explained by the critical model containing only IRI.

As shown in Table 55, regression results for BBI has similarity with IRI, indicating very strong and positive coefficients of determination but low and positive average Pearson's correlation coefficient of 0.17 (see Table 49). Here, the critical situation occurs in the model NGPL Class III. Thus, pavement loads are 50% higher than the static load when BBI is 0.4 and result twice the static load when it is above 0.5. The average R² is 0.92 (about 15% higher than IRI) so 92% of the variation in NGPL can be explained by the critical model containing only BBI.

4.3.2.4 MGPL vs. IRI & BBI

Table 56 and 57 presents the results of the regression analysis between IRI and BBI and MGPL, respectively.

Although linear regression models in Table 56 indicate very strong and positive coefficients of determination, correlation results in Table 49 shows that there

was a low negative linear relationship between NGPL and IRI, with average Pearson's correlation coefficient of -0.02.

Even so, a critical situation may be also identified. It occurs in the model MGPL Class I which considers high pavement load ratios at the main landing gear of the aircraft class I. Therefore, pavement loads are 50% higher than the static load when IRI is 3.5 m/km and also can be twice if it reaches 4.0 m/km. In addition, R^2 value of the critical model was 0.82 so 82% of the variation in MGPL can be explained by IRI.

Table 56 Linear regression analyses for MGPL vs. IRI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	IRI to reach 1.5 ratio	IRI to reach 2.0 ratio
MGPL Overall	IRI	$MGPL = (0.3373 * IRI)^2$	0.82	3.6	4.2
MGPL RMS	IRI	$MGPL = (0.2718 * IRI)^2$	0.76	4.5	5.2
MGPL MAX	IRI	$MGPL = (0.2738 * IRI)^2$	0.76	4.5	5.2
MGPL Class I	IRI	$MGPL = (0.3494 * IRI)^2$	0.82	3.5	4.0
MGPL Class II	IRI	$MGPL = (0.3235 * IRI)^2$	0.82	3.8	4.4
MGPL Class III	IRI	$MGPL = (0.3360 * IRI)^2$	0.82	3.6	4.2
MGPL Class IV	IRI	$MGPL = (0.3402 * IRI)^2$	0.82	3.6	4.2

Table 57 Linear regression analyses for MGPL vs. BBI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	BBI to reach 1.5 ratio	BBI to reach 2.0 ratio
MGPL Overall	BBI	$MGPL = (1.5805)^2 * BBI$	0.93	0.6	0.8
MGPL RMS	BBI	$MGPL = (1.0965)^2 * BBI$	0.89	1.2	1.7
MGPL MAX	BBI	$MGPL = (1.1732)^2 * BBI$	0.90	1.1	1.5
MGPL Class I	BBI	$MGPL = (1.6373)^2 * BBI$	0.93	0.6	0.7
MGPL Class II	BBI	$MGPL = (1.5159)^2 * BBI$	0.93	0.7	0.9
MGPL Class III	BBI	$MGPL = (1.5746)^2 * BBI$	0.93	0.6	0.8
MGPL Class IV	BBI	$MGPL = (1.5943)^2 * BBI$	0.93	0.6	0.8

The same can be observed in Table 57. Here, BBI models have stronger and positive coefficients of determination than IRI. However, correlation results in Table 49 show that there was a low negative linear relationship between NGPL and BBI, with average Pearson's correlation coefficient of -0.02. The critical situation also occurs in the model MGPL Class I. Therefore, pavement loads are 50% higher than the static load when BBI is 0.6 and can be twice if it reaches 0.7. In addition, R^2 value

of the critical model was 0.93 so 93% of the variation in MGPL can be explained by BBI.

4.3.2.5 RGPL vs. IRI & BBI

Table 58 and 59 presents the final regression results for IRI and BBI as a function of MGPL, respectively.

As can be seen, the linear regression models indicate very strong and positive coefficients of determination. However, correlation results in Table 49 show that there was a low positive linear relationship between NGPL and IRI, with average Pearson's correlation coefficient of 0.02. Here, the critical situation occurs in the model RGPL Overall which considers RMS and MAX ratios at the rear landing gear of the aircraft class IV. In this case, pavement loads are 50% higher than the static load when IRI is 3.6 m/km and also can be twice if it reaches 4.1 m/km. In addition, R^2 value of the critical model was 0.82 so 82% of the variation in MGPL can be explained by IRI. The R^2 value of the critical model was the same than in MGPL (0.82).

Table 58 Linear regression analyses for RGPL vs. IRI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	IRI to reach 1.5 ratio	IRI to reach 2.0 ratio
RGPL Overall	IRI	$RGPL = (0.3418 * IRI)^2$	0.82	3.6	4.1
RGPL RMS	IRI	$RGPL = (0.2756 * IRI)^2$	0.76	4.4	5.1
RGPL MAX	IRI	$RGPL = (0.2782 * IRI)^2$	0.76	4.4	5.1

Table 59 Linear regression analyses for RGPL vs. BBI; by overall, RMS, MAX, and aircraft class

Dependent Variable	Independent Variable	Equation	R^2	BBI to reach 1.5 ratio	BBI to reach 2.0 ratio
RGPL Overall	BBI	$RGPL = (1.6019)^2 * BBI$	0.93	0.6	0.8
RGPL RMS	BBI	$RGPL = (1.1121)^2 * BBI$	0.89	1.2	1.6
RGPL MAX	BBI	$RGPL = (1.1545)^2 * BBI$	0.90	1.1	1.5

RGPL regression results for BBI are very similar to MGPL. Table 59 shows that, for the critical model, pavement loads are 50% higher than the static load when BBI is 0.6 and also can be twice if it reaches 0.8. The R^2 value of the critical model was the same than in MGPL (0.93).

4.3.3 Regression Summary (critical models)

The following tables present those regression models that were considered critical.

4.3.3.1 VACP & VACG

Table 60 shows the critical models for VACP and VACG based on IRI and BBI. As can be seen, VACP evidenced to be more critical than VACG.

Table 60 Regression summary of critical models for VACP and VACG

Dependent Variable	Independent Variable	Equation	R ²	IRI/BBI to reach 0.35 g	IRI/BBI to reach 0.40 g
VACP MAX	IRI	$VACP = (0.1729 * IRI)^2$	0.78	3.4	3.7
VACP MAX	BBI	$VACP = (1.2970)^2 * BBI$	0.91	0.2	0.2
VACG MAX	IRI	$VACG = (0.1249 * IRI)^2$	0.73	4.7	5.1
VACG MAX	BBI	$VACG = (1.0972)^2 * BBI$	0.84	0.3	0.3

In this context, the IRI and BBI when VACP reach 0.40 g are 3.7 m/km and 0.2, respectively.

4.3.3.2 NGPL, MGPL, & RGPL

Table 61 shows the critical models for NGPL, MGPL, and RGPL based on IRI and BBI. As can be seen, NGPL evidenced to be more critical than MGPL and RGPL.

Table 61 Regression summary of critical models for NGPL, MGPL, and RGPL

Dependent Variable	Independent Variable	Equation	R ²	IRI/BBI to reach 1.5 ratio	IRI/BBI to reach 2.0 ratio
NGPL Class III	IRI	$NGPL = (0.4259 * IRI)^2$	0.82	2.9	3.3
NGPL Class III	BBI	$NGPL = (1.9968)^2 * BBI$	0.93	0.4	0.5
MGPL Class I	IRI	$MGPL = (0.3494 * IRI)^2$	0.82	3.5	4.0
MGPL Class I	BBI	$MGPL = (1.6373)^2 * BBI$	0.93	0.6	0.7
RGPL Overall	IRI	$RGPL = (0.3418 * IRI)^2$	0.82	3.6	4.1
RGPL Overall	BBI	$RGPL = (1.6019)^2 * BBI$	0.93	0.6	0.8

Accordingly, the IRI and BBI when NGPL reach 0.40 g are 3.3 m/km and 0.2, respectively.

4.4 CLASSIFICATIONS BASED ON AIRCRAFT DYNAMIC RESPONSES

As discussed before, excessive vertical accelerations in the aircraft cockpit affect instrument accuracy, decrease the pilot's ability to read the instruments, and produce airframe metal fatigue damage and dynamic stressing. Likewise, excessive pavement loads encountered in service and the consequence accumulation of damage reduces the fatigue life of the landing gear systems and aircraft structure. Therefore, there is a need for alternative classifications that taking into account the effect of aircraft dynamic responses due to airport pavement roughness.

As was seen in previous analyses, BBI showed a higher correlation with aircraft dynamic responses than IRI. However, it was also observed that the BBI scale needs to be evaluated and adjusted once excessive vertical accelerations at the aircraft cockpit can occur when BBI is equal to or greater than 0.2, that is at the lower zone of the Acceptable region in the BBI classification. Consequently, before to propose an alternative pavement roughness classification based on BBI and aircraft dynamic responses it is strongly recommended the evaluation and adjust of the BBI scale. On the other hand, IRI is able to evaluate airport pavement roughness, even just for bumps less than 100 m in length, due to the nature of its mathematical model (quarter-car model).

In this context, there are two interesting situations. The first one is that BBI was created specifically to airport pavements, but it has limitations to evaluate airport pavement roughness. The second one is that although the IRI has been indicated to highway pavements and its mathematical model is based on a quarter-car model that cannot be compared with the dynamic behavior of an aircraft, it has shown being capable to evaluate airport pavement roughness characterized by bumps up to 100 m in length.

4.4.1 Classifications Based On Current Critical Limits

Tables 62 and 63 show two IRI classifications that take into account two current critical limits, one of them suggested by Sayers & Karamihas (1998) for $IRI = 2.0$ m/km and the other one established by ANAC (2019) for $IRI = 2.5$ m/km. The classification in Table 63 was used in this study as a reference for the analyses performed before, in order to facilitate the visualization of the IRI values through

categories based on roughness severity. The last column in the tables suggests appropriate general maintenance and rehabilitation activities for each category.

Table 62 Classification for critical IRI of 2.0 m/km, based on SAYERS

Category	IRI (m/km)	Maintenance & Rehabilitation activities
Very Good	< 0.5	Do nothing
Good	0.5 to 1.0	Preventive maintenance
Regular	1.0 to 1.5	Corrective maintenance
Poor	1.5 to 2.0	Minor Rehabilitation
Very Poor	> 2.0	Major Rehabilitation

Table 63 Classification for critical IRI of 2.5 m/km, based on ANAC

Category	IRI (m/km)	Maintenance & Rehabilitation activities
Very Good	< 1.0	Do nothing
Good	1.0 to 1.5	Preventive maintenance
Regular	1.5 to 2.0	Corrective maintenance
Poor	2.0 to 2.5	Minor Rehabilitation
Very Poor	> 2.5	Major Rehabilitation

4.4.2 Proposed Alternative Classifications Based On Aircraft Dynamic Responses

Tables 64, 65, and 66 are proposed classifications based on the critical limits obtained from the regression analysis for NGPL (IRI = 3.3 m/km), the average between NGPL and VACP (IRI = 3.5 m/km), and from the regression analysis for VACP (IRI = 3.7 m/km), respectively. The idea of the last three classifications is to support airport managers and engineers, from a network level point of view, in the decision making process of an Airport Pavement Management System. The third column in the tables is the estimated aircraft dynamic response (VACP and/or NGPL values) for each IRI value.

As can be seen, Tables 64 and 66 present classifications for IRI that takes into account critical vertical accelerations and high pavement load ratios, respectively. Conversely, the classification in Table 65 was constructed for practical purposes and it is based on the average of those critical limits, resulting in IRI of 3.5 m/km. These

classifications were constructed from the expected IRI when cockpit accelerations are equal to 0.40 g (3.7 m/km – see Table 60) as well as when nose gear pavement loads are about twice than static loads (3.3 m/km – see Table 61). Thus, the last three classifications are based on the critical limits of 3.3, 3.5, and 3.7 m/km, respectively. It can be observed that the average of these critical limits is about 75% and 40% higher than the limits suggested by Sayers & Karamihas (2.0 m/km) and ANAC (2.5 m/km), respectively.

Table 64 Classification for critical IRI of 3.3 m/km, based on NGPL

Category	IRI (m/km)	Estimated NGPL (ratio) $NGPL=(0.4259*IRI)^2$	Maintenance & Rehabilitation activities
Very Good	< 1.7	< 0.5	Do nothing
Good	1.7 to 2.4	0.5 – 1.0	Preventive maintenance
Regular	2.4 to 2.9	1.0 – 1.5	Corrective maintenance
Poor	2.9 to 3.3	1.5 – 2.0	Minor Rehabilitation
Very Poor	> 3.3	> 2.0	Major Rehabilitation

Table 65 Classification for critical IRI of 3.5 m/km, based on AVERAGE between VACP and NGPL

Category	IRI (m/km)	Estimated VACP (g) $VACP=(0.1729*IRI)^2$	Estimated NGPL (ratio) $NGPL=(0.4259*IRI)^2$	Maintenance & Rehabilitation activities
Very Good	< 2.0	< 0.12	< 0.73	Do nothing
Good	2.0 to 2.5	0.12 – 0.19	0.73 – 1.13	Preventive maintenance
Regular	2.5 to 3.0	0.19 – 0.27	1.13 – 1.63	Corrective maintenance
Poor	3.0 to 3.5	0.27 – 0.37	1.63 – 2.22	Minor Rehabilitation
Very Poor	> 3.5	> 0.37	> 2.22	Major Rehabilitation

Table 66 Classification for critical IRI of 3.7 m/km, based on VACP

Category	IRI (m/km)	Estimated VACP (g) $VACP=(0.1729*IRI)^2$	Maintenance & Rehabilitation activities
Very Good	< 1.8	< 0.10	Do nothing
Good	1.8 to 2.6	0.10 – 0.20	Preventive maintenance
Regular	2.6 to 3.2	0.20 – 0.30	Corrective maintenance
Poor	3.2 to 3.7	0.30 – 0.40	Minor Rehabilitation
Very Poor	> 3.7	> 0.40	Major Rehabilitation

In this context, classifications with five categories allows airport managers and engineers to make decisions in a flexible way once an intermediate number of categories facilitate the identification of the pavement condition in a network-level pavement management system.

The choice of the ideal classification is responsibility of the airport authorities and depends directly on the technical needs of a specific airport network as well as on the priorities established by the decision-makers. Furthermore, it is extremely important to keep in mind that the use of any of these alternative classifications should be accompanied by the evaluation of the pavement elevation profile and that simulations of dynamic responses by ProFAA software also should be carried out.

5 CASE STUDY

This section presents an example for the implementation of the IRI classifications discussed above. To do that, an airport network comprised of nine airport runways of asphalt concrete was studied. Each runway was divided into sections of 100 m in length, resulting in 172 pavement sections. Pavement roughness evaluations were performed at the end of 2013 for the whole network and measures took place during the night and under cloudy weather and temperature of 18°C.

5.1 PAVEMENT ROUGHNESS MEASUREMENTS

The company hired to conduct these evaluations used a multi-laser profiler vehicle (Class 2 device) to measure pavement roughness and to compute the IRI in m/km (see Fig. 76a). The device measured the pavement roughness along the runways at 3m left and 3m right offsets respect to the centerline, with five measures spaced transversely every 0.6 m (one measure for each laser in the profiler beam), as shown in Figure 76b. However, the IRI was not computed for the first and last sections of each pavement profile in order to avoid errors in the measurements that can occur while the vehicle reaches the test speed. For practical purposes, the case study is based on IRI peak values in each pavement section.

Figure 76 a) Class 2 device used to measure IRI; b) Pathway of IRI measures by the Class 2 device along an airport runway

5.2 AIRPORT RUNWAYS DATA

The airport runways were ordered from minor to major according to their IRI Profile value and then were named alphabetically, as shown in Table 67. The table provides the runway length and width, as well as the IRI profile value in m/km (RMS of the IRI values by sections) and the standard deviation. Note that the airport network has 815,400 m² of asphalt pavement distributed in nine runways with lengths ranging from 1300 to 3000m and IRI Profile values varying from 1.19 and 4.01 m/km. In a general context, it is evident that more than 60% of the runways exceed the current critical limits that have been suggested by Sayers and ANAC. As an important fact, all the runways presented in this example are currently in operation.

Table 67 Airport runways used in the case study

Airport Runway	Runway Length (m)	Runway Width (m)	IRI Profile (m/km)	St. Dev.
A	1400	30	1.19	0.29
B	1500	42	1.44	0.31
C	2000	45	1.96	0.27
D	1500	45	2.40	0.24
E	2300	45	2.60	0.58
F	2600	45	2.93	0.53
G	3100	42	3.27	0.50
H	3000	45	3.70	0.68
I	1600	42	4.01	0.65

5.3 IRI CLASSIFICATIONS AND ESTIMATED PARAMETERS BY AIRPORT RUNWAY

Based on colored scales, Tables 68 to 76 illustrates the five IRI categories (Very Good, Good, Regular, Poor, and Very Poor) for each IRI classifications discussed before (SAYERS, ANAC, NGPL, AVERAGE, and VACP), by pavement sections and for the nine runways in the study, respectively.

The tables also show the estimated parameters such as the BBI as well as the aircraft dynamic responses (VACP, VACG, NGPL, MGPL, and RGPL) that were calculated with the equations given in Tables 60 and 61. Estimated vertical accelerations exceeding 0.35 and 0.40 g as well as estimated pavement load ratios higher than 1.5 and 2.0 were also highlighted with the colored scale shown in Figure 77.

Critical Vertical Accelerations (g)	
0,35	0,40
High Pavement Loads (ratio)	
1,50	2,00

Figure 77 Colored scale used to highlight critical estimated values of aircraft dynamics responses

It can be observed in Table 68 that IRI sections in runway A vary from 0.89 to 1.90 m/km and there are no sections exceeding vertical accelerations or with high pavement load ratios. According to Sayers's classification, 92% of the pavement in the runway is "Very Good" IRI and just 8% (one section) is "Poor". However, when ANAC's classification is used only 17% is "Very Good" and 66% of the pavement sections are "Good" and 17% are "Regular". Conversely, if NGPL, AVERAGE, and VACP are considered it is evident that sections that were considered "Regular" or "Poor" by the other classifications are now predominantly "Very Good". In this case, the alternative classifications would reduce the maintenance and rehabilitation costs, because the sections would not need interventions because they do not have excessive vertical accelerations and/or high pavement load ratios.

Table 68 IRI classifications and estimated BBI and aircraft dynamics responses for runway A

Runway A												
Runway Length	IRI (m/km)	IRI Classification (m/km)					Estimated parameters					
		SAYERS 2.0	ANAC 2.5	NGPL 3.3	AVERAGE 3.5	VACP 3.7	BBI	VACP (g)	VACG (g)	NGPL (ratio)	MGPL (ratio)	RGPL (ratio)
0+100	-	-	-	-	-	-	-	-	-	-	-	-
0+200	1,60	1,60	1,60	1,60	1,60	1,60	0,1613	0,0765	0,0399	0,3125	0,3125	0,2991
0+300	1,13	1,13	1,13	1,13	1,13	1,13	0,1139	0,0382	0,0199	0,1559	0,1559	0,1492
0+400	1,01	1,01	1,01	1,01	1,01	1,01	0,1018	0,0305	0,0159	0,1245	0,1245	0,1192
0+500	1,12	1,12	1,12	1,12	1,12	1,12	0,1129	0,0375	0,0196	0,1531	0,1531	0,1465
0+600	1,01	1,01	1,01	1,01	1,01	1,01	0,1018	0,0305	0,0159	0,1245	0,1245	0,1192
0+700	1,06	1,06	1,06	1,06	1,06	1,06	0,1068	0,0336	0,0175	0,1372	0,1372	0,1313
0+800	1,07	1,07	1,07	1,07	1,07	1,07	0,1079	0,0342	0,0179	0,1398	0,1398	0,1338
0+900	1,03	1,03	1,03	1,03	1,03	1,03	0,1038	0,0317	0,0166	0,1295	0,1295	0,1239
0+1000	1,04	1,04	1,04	1,04	1,04	1,04	0,1048	0,0323	0,0169	0,1320	0,1320	0,1264
0+1100	0,98	0,98	0,98	0,98	0,98	0,98	0,0988	0,0287	0,0150	0,1172	0,1172	0,1122
0+1200	0,89	0,89	0,89	0,89	0,89	0,89	0,0897	0,0237	0,0124	0,0967	0,0967	0,0925
0+1300	1,90	1,90	1,90	1,90	1,90	1,90	0,1915	0,1079	0,0563	0,4407	0,4407	0,4217
0+1400	-	-	-	-	-	-	-	-	-	-	-	-

The same occurs in runway B shown in Table 69. As can be seen, there is one section considered "Very Poor" by Sayers's classification. However, the IRI of this section does not reach the critical limit of vertical accelerations. On the other hand, when any alternative classification is used, the section considered as "Very Poor" upgrades to a "Good" condition.

Table 71 shows the IRI for runway D. In this case and based on Sayer's classification, 92% of the sections are "Very Poor" and the remaining 8% is "Poor". Spite of IRI varies from 1.95 to 2.88 m/km, alternative classification based on VACP, for example, allow to improve this condition and now 77% of the sections are "Good" and the remaining 23% are "Regular". Similarly, Table 72 shows the IRI for runway E.

Table 71 IRI classifications and estimated BBI and aircraft dynamics responses for runway D

[illegible]

Table 72 IRI classifications and estimated BBI and aircraft dynamics responses for runway E

[illegible]

Table 73 IRI classifications and estimated BBI and aircraft dynamics responses for runway F

Runway F												
Runway Length	IRI (m/km)	IRI Classification (m/km)					Estimated parameters					
		SAYERS 2.0	ANAC 2.5	NGPL 3.3	AVERAGE 3.5	VACP 3.7	BBI	VACP (g)	VACG (g)	NGPL (ratio)	MGPL (ratio)	RGPL (ratio)
0+100	-	-	-	-	-	-	-	-	-	-	-	-
0+200	3,07	3,07	3,07	3,07	3,07	3,07	0,3095	0,2818	0,1470	1,1506	1,1506	1,1011
0+300	2,30	2,30	2,30	2,30	2,30	2,30	0,2318	0,1581	0,0825	0,6458	0,6458	0,6180
0+400	2,87	2,87	2,87	2,87	2,87	2,87	0,2893	0,2462	0,1285	1,0056	1,0056	0,9623
0+500	2,91	2,91	2,91	2,91	2,91	2,91	0,2933	0,2531	0,1321	1,0338	1,0338	0,9893
0+600	2,61	2,61	2,61	2,61	2,61	2,61	0,2631	0,2036	0,1063	0,8316	0,8316	0,7958
0+700	2,30	2,30	2,30	2,30	2,30	2,30	0,2318	0,1581	0,0825	0,6458	0,6458	0,6180
0+800	2,73	2,73	2,73	2,73	2,73	2,73	0,2752	0,2228	0,1163	0,9099	0,9099	0,8707
0+900	2,58	2,58	2,58	2,58	2,58	2,58	0,2601	0,1990	0,1038	0,8126	0,8126	0,7776
0+1000	3,41	3,41	3,41	3,41	3,41	3,41	0,3437	0,3476	0,1814	1,4196	1,4196	1,3585
0+1100	2,50	2,50	2,50	2,50	2,50	2,50	0,2520	0,1868	0,0975	0,7630	0,7630	0,7302
0+1200	2,70	2,70	2,70	2,70	2,70	2,70	0,2722	0,2179	0,1137	0,8900	0,8900	0,8517
0+1300	2,91	2,91	2,91	2,91	2,91	2,91	0,2933	0,2531	0,1321	1,0338	1,0338	0,9893
0+1400	3,37	3,37	3,37	3,37	3,37	3,37	0,3397	0,3395	0,1772	1,3865	1,3865	1,3268
0+1500	4,51	4,51	4,51	4,51	4,51	4,51	0,4546	0,6081	0,3173	2,4831	2,4831	2,3763
0+1600	3,00	3,00	3,00	3,00	3,00	3,00	0,3024	0,2690	0,1404	1,0987	1,0987	1,0514
0+1700	2,62	2,62	2,62	2,62	2,62	2,62	0,2641	0,2052	0,1071	0,8380	0,8380	0,8019
0+1800	3,07	3,07	3,07	3,07	3,07	3,07	0,3095	0,2818	0,1470	1,1506	1,1506	1,1011
0+1900	4,01	4,01	4,01	4,01	4,01	4,01	0,4042	0,4807	0,2508	1,9631	1,9631	1,8786
0+2000	2,43	2,43	2,43	2,43	2,43	2,43	0,2449	0,1765	0,0921	0,7209	0,7209	0,6899
0+2100	2,74	2,74	2,74	2,74	2,74	2,74	0,2762	0,2244	0,1171	0,9165	0,9165	0,8771
0+2200	2,16	2,16	2,16	2,16	2,16	2,16	0,2177	0,1395	0,0728	0,5696	0,5696	0,5451
0+2300	2,78	2,78	2,78	2,78	2,78	2,78	0,2802	0,2310	0,1206	0,9435	0,9435	0,9029
0+2400	2,97	2,97	2,97	2,97	2,97	2,97	0,2994	0,2637	0,1376	1,0769	1,0769	1,0305
0+2500	3,16	3,16	3,16	3,16	3,16	3,16	0,3185	0,2985	0,1558	1,2190	1,2190	1,1666
0+2600	-	-	-	-	-	-	-	-	-	-	-	-

It is evident that alternative classifications can help airport managers and engineers to make decisions based on additional criteria, such as aircraft dynamic responses, mainly because the alternative classifications are much more representative of the condition observed in the field.

Another clear example of that can be seen in Table 73 that shows the IRI for the runway F. It can be observed that IRI values ranging from 2.16 to 4.51 m/km and according to Sayer's classification all the pavement sections are "Very Poor". However, the use of the VACP classification improves this condition reducing to 8% the pavement sections considered as "Very Poor". Furthermore, the VACP classification allows identifying those sections that exceeds 0.40 g and generates high pavement load ratios. As can be seen in Table 73, the sections located at the stations 0+1500 and 0+1900 are sections that exceed this critical limit and, therefore, they should be a priority in the maintenance and rehabilitation program.

Table 74 IRI classifications and estimated BBI and aircraft dynamics responses for runway G

Runway Length	IRI (m/km)	Runway G										
		IRI Classification (m/km)					Estimated parameters					
		SAYERS 2.0	ANAC 2.5	NGPL 3.3	AVERAGE 3.5	VACP 3.7	BBI	VACP (g)	VACG (g)	NGPL (ratio)	MGPL (ratio)	RGPL (ratio)
0+100	-	-	-	-	-	-	-	-	-	-	-	-
0+200	3,15	3,15	3,15	3,15	3,15	3,15	0,3175	0,2966	0,1548	1,2113	1,2113	1,1592
0+300	3,21	3,21	3,21	3,21	3,21	3,21	0,3236	0,3080	0,1607	1,2579	1,2579	1,2038
0+400	3,07	3,07	3,07	3,07	3,07	3,07	0,3095	0,2818	0,1470	1,1506	1,1506	1,1011
0+500	2,69	2,69	2,69	2,69	2,69	2,69	0,2712	0,2163	0,1129	0,8834	0,8834	0,8454
0+600	2,69	2,69	2,69	2,69	2,69	2,69	0,2712	0,2163	0,1129	0,8834	0,8834	0,8454
0+700	2,61	2,61	2,61	2,61	2,61	2,61	0,2631	0,2036	0,1063	0,8316	0,8316	0,7958
0+800	2,94	2,94	2,94	2,94	2,94	2,94	0,2964	0,2584	0,1348	1,0552	1,0552	1,0098
0+900	3,06	3,06	3,06	3,06	3,06	3,06	0,3084	0,2799	0,1461	1,1431	1,1431	1,0939
0+1000	3,15	3,15	3,15	3,15	3,15	3,15	0,3175	0,2966	0,1548	1,2113	1,2113	1,1592
0+1100	3,00	3,00	3,00	3,00	3,00	3,00	0,3024	0,2690	0,1404	1,0987	1,0987	1,0514
0+1200	2,59	2,59	2,59	2,59	2,59	2,59	0,2611	0,2005	0,1046	0,8189	0,8189	0,7837
0+1300	2,85	2,85	2,85	2,85	2,85	2,85	0,2873	0,2428	0,1267	0,9916	0,9916	0,9489
0+1400	4,71	4,71	4,71	4,71	4,71	4,71	0,4748	0,6632	0,3461	2,7082	2,7082	2,5917
0+1500	3,35	3,35	3,35	3,35	3,35	3,35	0,3377	0,3355	0,1751	1,3700	1,3700	1,3111
0+1600	3,40	3,40	3,40	3,40	3,40	3,40	0,3427	0,3456	0,1803	1,4112	1,4112	1,3505
0+1700	3,39	3,39	3,39	3,39	3,39	3,39	0,3417	0,3435	0,1793	1,4030	1,4030	1,3426
0+1800	2,41	2,41	2,41	2,41	2,41	2,41	0,2429	0,1736	0,0906	0,7091	0,7091	0,6785
0+1900	3,16	3,16	3,16	3,16	3,16	3,16	0,3185	0,2985	0,1558	1,2190	1,2190	1,1666
0+2000	2,97	2,97	2,97	2,97	2,97	2,97	0,2994	0,2637	0,1376	1,0769	1,0769	1,0305
0+2100	3,68	3,68	3,68	3,68	3,68	3,68	0,3709	0,4048	0,2113	1,6533	1,6533	1,5821
0+2200	3,76	3,76	3,76	3,76	3,76	3,76	0,3790	0,4226	0,2205	1,7259	1,7259	1,6517
0+2300	3,50	3,50	3,50	3,50	3,50	3,50	0,3528	0,3662	0,1911	1,4955	1,4955	1,4311
0+2400	3,64	3,64	3,64	3,64	3,64	3,64	0,3669	0,3961	0,2067	1,6175	1,6175	1,5479
0+2500	4,27	4,27	4,27	4,27	4,27	4,27	0,4304	0,5451	0,2844	2,2259	2,2259	2,1301
0+2600	3,34	3,34	3,34	3,34	3,34	3,34	0,3367	0,3335	0,1740	1,3619	1,3619	1,3033
0+2700	2,90	2,90	2,90	2,90	2,90	2,90	0,2923	0,2514	0,1312	1,0267	1,0267	0,9825
0+2800	3,66	3,66	3,66	3,66	3,66	3,66	0,3689	0,4005	0,2090	1,6353	1,6353	1,5650
0+2900	3,38	3,38	3,38	3,38	3,38	3,38	0,3407	0,3415	0,1782	1,3947	1,3947	1,3347
0+3000	2,87	2,87	2,87	2,87	2,87	2,87	0,2893	0,2462	0,1285	1,0056	1,0056	0,9623
0+3100	-	-	-	-	-	-	-	-	-	-	-	-

It is important to note that the use of alternative classifications allows to establishing technical criteria that supports the decision making process in a network level APMS. Alternative classifications can help airport managers and engineers to identify pavement sections that are not yet candidates for maintenance and rehabilitation activities but that demand some attention to avoid excessive aircraft dynamic responses. Table 74 to 76 shows the IRI for runways G, H, and I, respectively, where the number of critical sections has increased significantly.

Table 75 IRI classifications and estimated BBI and aircraft dynamics responses for runway H

Runway H												
Runway Length	IRI (m/km)	IRI Classification (m/km)					Estimated parameters					
		SAYERS 2.0	ANAC 2.5	NGPL 3.3	AVERAGE 3.5	VACP 3.7	BBI	VACP (g)	VACG (g)	NGPL (ratio)	MGPL (ratio)	RGPL (ratio)
0+100	-	-	-	-	-	-	-	-	-	-	-	-
0+200	3,79	3,79	3,79	3,79	3,79	3,79	0,3820	0,4294	0,2241	1,7536	1,7536	1,6781
0+300	4,20	4,20	4,20	4,20	4,20	4,20	0,4234	0,5273	0,2752	2,1535	2,1535	2,0608
0+400	4,00	4,00	4,00	4,00	4,00	4,00	0,4032	0,4783	0,2496	1,9533	1,9533	1,8692
0+500	3,86	3,86	3,86	3,86	3,86	3,86	0,3891	0,4454	0,2324	1,8189	1,8189	1,7407
0+600	4,58	4,58	4,58	4,58	4,58	4,58	0,4617	0,6271	0,3272	2,5608	2,5608	2,4506
0+700	4,14	4,14	4,14	4,14	4,14	4,14	0,4173	0,5124	0,2674	2,0924	2,0924	2,0024
0+800	3,97	3,97	3,97	3,97	3,97	3,97	0,4002	0,4712	0,2459	1,9241	1,9241	1,8413
0+900	3,14	3,14	3,14	3,14	3,14	3,14	0,3165	0,2947	0,1538	1,2037	1,2037	1,1519
0+1000	4,37	4,37	4,37	4,37	4,37	4,37	0,4405	0,5709	0,2979	2,3314	2,3314	2,2310
0+1100	3,31	3,31	3,31	3,31	3,31	3,31	0,3336	0,3275	0,1709	1,3375	1,3375	1,2800
0+1200	3,30	3,30	3,30	3,30	3,30	3,30	0,3326	0,3256	0,1699	1,3295	1,3295	1,2722
0+1300	2,91	2,91	2,91	2,91	2,91	2,91	0,2933	0,2531	0,1321	1,0338	1,0338	0,9893
0+1400	4,53	4,53	4,53	4,53	4,53	4,53	0,4566	0,6135	0,3201	2,5052	2,5052	2,3974
0+1500	2,68	2,68	2,68	2,68	2,68	2,68	0,2701	0,2147	0,1120	0,8768	0,8768	0,8391
0+1600	2,92	2,92	2,92	2,92	2,92	2,92	0,2943	0,2549	0,1330	1,0409	1,0409	0,9961
0+1700	2,49	2,49	2,49	2,49	2,49	2,49	0,2510	0,1853	0,0967	0,7569	0,7569	0,7243
0+1800	2,79	2,79	2,79	2,79	2,79	2,79	0,2812	0,2327	0,1214	0,9503	0,9503	0,9094
0+1900	2,60	2,60	2,60	2,60	2,60	2,60	0,2621	0,2021	0,1055	0,8253	0,8253	0,7898
0+2000	3,06	3,06	3,06	3,06	3,06	3,06	0,3084	0,2799	0,1461	1,1431	1,1431	1,0939
0+2100	3,00	3,00	3,00	3,00	3,00	3,00	0,3024	0,2690	0,1404	1,0987	1,0987	1,0514
0+2200	3,73	3,73	3,73	3,73	3,73	3,73	0,3760	0,4159	0,2170	1,6985	1,6985	1,6254
0+2300	3,71	3,71	3,71	3,71	3,71	3,71	0,3740	0,4115	0,2147	1,6803	1,6803	1,6080
0+2400	4,77	4,77	4,77	4,77	4,77	4,77	0,4808	0,6802	0,3549	2,7777	2,7777	2,6582
0+2500	3,81	3,81	3,81	3,81	3,81	3,81	0,3840	0,4340	0,2265	1,7721	1,7721	1,6959
0+2600	3,98	3,98	3,98	3,98	3,98	3,98	0,4012	0,4735	0,2471	1,9338	1,9338	1,8506
0+2700	4,80	4,80	4,80	4,80	4,80	4,80	0,4838	0,6888	0,3594	2,8127	2,8127	2,6917
0+2800	3,95	3,95	3,95	3,95	3,95	3,95	0,3982	0,4664	0,2434	1,9048	1,9048	1,8228
0+2900	4,18	4,18	4,18	4,18	4,18	4,18	0,4213	0,5223	0,2726	2,1330	2,1330	2,0413
0+3000	-	-	-	-	-	-	-	-	-	-	-	-

Table 76 IRI classifications and estimated BBI and aircraft dynamics responses for runway I

[illegible]

5.4 SUMMARY OF CURRENT & ALTERNATIVE IRI CLASSIFICATIONS

Table 77 is a summary of the IRI classifications for the airport network.

Table 77 Classifications summary for the airport network

Classification	Runway	Length (m)																																
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800	2900	3000	3100		
SAYERS (2.0 m/km)	A	-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	B	-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-	
	D	-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	E	-	2.60	2.08	1.72	1.81	2.01	2.72	2.39	1.99	3.13	2.78	3.66	3.39	1.95	2.16	1.92	2.53	2.04	2.80	2.86	3.19	3.23	-	-	-	-	-	-	-	-	-	-	
	F	-	3.07	2.30	2.87	2.91	2.61	2.30	2.73	2.58	3.41	2.50	2.70	2.91	3.37	4.51	3.00	2.62	3.07	4.01	2.43	2.74	2.16	2.78	2.97	3.16	-	-	-	-	-	-	-	
	G	-	3.15	3.21	3.07	2.69	2.69	2.61	2.94	3.06	3.15	3.00	2.59	2.85	4.71	3.35	3.40	3.39	2.41	3.16	2.97	3.68	3.76	3.50	3.64	4.27	3.34	2.90	3.66	3.38	2.87	-	-	
	H	-	3.79	4.20	4.00	3.86	4.58	4.14	3.97	3.14	4.37	3.31	3.30	2.91	4.53	2.68	2.92	2.49	2.79	2.60	3.06	3.00	3.73	3.71	4.77	3.81	3.98	4.80	3.95	4.18	-	-	-	
	I	-	3.89	4.13	3.71	3.97	3.01	3.71	3.87	4.38	3.33	2.93	5.31	4.90	4.27	3.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	A	-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ANAC (2.5 m/km)	B	-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-	
	D	-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	E	-	2.60	2.08	1.72	1.81	2.01	2.72	2.39	1.99	3.13	2.78	3.66	3.39	1.95	2.16	1.92	2.53	2.04	2.80	2.86	3.19	3.23	-	-	-	-	-	-	-	-	-	-	
	F	-	3.07	2.30	2.87	2.91	2.61	2.30	2.73	2.58	3.41	2.50	2.70	2.91	3.37	4.51	3.00	2.62	3.07	4.01	2.43	2.74	2.16	2.78	2.97	3.16	-	-	-	-	-	-	-	
	G	-	3.15	3.21	3.07	2.69	2.69	2.61	2.94	3.06	3.15	3.00	2.59	2.85	4.71	3.35	3.40	3.39	2.41	3.16	2.97	3.68	3.76	3.50	3.64	4.27	3.34	2.90	3.66	3.38	2.87	-	-	
	H	-	3.79	4.20	4.00	3.86	4.58	4.14	3.97	3.14	4.37	3.31	3.30	2.91	4.53	2.68	2.92	2.49	2.79	2.60	3.06	3.00	3.73	3.71	4.77	3.81	3.98	4.80	3.95	4.18	-	-		
	I	-	3.89	4.13	3.71	3.97	3.01	3.71	3.87	4.38	3.33	2.93	5.31	4.90	4.27	3.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	A	-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	B	-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
NGPL (3.3 m/km)	C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-	
	D	-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	E	-	2.60	2.08	1.72	1.81	2.01	2.72	2.39	1.99	3.13	2.78	3.66	3.39	1.95	2.16	1.92	2.53	2.04	2.80	2.86	3.19	3.23	-	-	-	-	-	-	-	-	-		
	F	-	3.07	2.30	2.87	2.91	2.61	2.30	2.73	2.58	3.41	2.50	2.70	2.91	3.37	4.51	3.00	2.62	3.07	4.01	2.43	2.74	2.16	2.78	2.97	3.16	-	-	-	-	-	-	-	
	G	-	3.15	3.21	3.07	2.69	2.69	2.61	2.94	3.06	3.15	3.00	2.59	2.85	4.71	3.35	3.40	3.39	2.41	3.16	2.97	3.68	3.76	3.50	3.64	4.27	3.34	2.90	3.66	3.38	2.87	-	-	
	H	-	3.79	4.20	4.00	3.86	4.58	4.14	3.97	3.14	4.37	3.31	3.30	2.91	4.53	2.68	2.92	2.49	2.79	2.60	3.06	3.00	3.73	3.71	4.77	3.81	3.98	4.80	3.95	4.18	-	-	-	
	I	-	3.89	4.13	3.71	3.97	3.01	3.71	3.87	4.38	3.33	2.93	5.31	4.90	4.27	3.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	A	-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	B	-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	AVERAGE (3.5 m/km)	C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-
D		-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
E		-	2.60	2.08	1.72	1.81	2.01	2.72	2.39	1.99	3.13	2.78	3.66	3.39	1.95	2.16	1.92	2.53	2.04	2.80	2.86	3.19	3.23	-	-	-	-	-	-	-	-	-		
F		-	3.07	2.30	2.87	2.91	2.61	2.30	2.73	2.58	3.41	2.50	2.70	2.91	3.37	4.51	3.00	2.62	3.07	4.01	2.43	2.74	2.16	2.78	2.97	3.16	-	-	-	-	-	-	-	
G		-	3.15	3.21	3.07	2.69	2.69	2.61	2.94	3.06	3.15	3.00	2.59	2.85	4.71	3.35	3.40	3.39	2.41	3.16	2.97	3.68	3.76	3.50	3.64	4.27	3.34	2.90	3.66	3.38	2.87	-	-	
H		-	3.79	4.20	4.00	3.86	4.58	4.14	3.97	3.14	4.37	3.31	3.30	2.91	4.53	2.68	2.92	2.49	2.79	2.60	3.06	3.00	3.73	3.71	4.77	3.81	3.98	4.80	3.95	4.18	-	-	-	
I		-	3.89	4.13	3.71	3.97	3.01	3.71	3.87	4.38	3.33	2.93	5.31	4.90	4.27	3.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
A		-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
B		-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
VACP (3.7 m/km)		C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-
	D	-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	E	-	2.60	2.08	1.72	1.81	2.01	2.72	2.39	1.99	3.13	2.78	3.66	3.39	1.95	2.16	1.92	2.53	2.04	2.80	2.86	3.19	3.23	-	-	-	-	-	-	-	-	-		
	F	-	3.07	2.30	2.87	2.91	2.61	2.30	2.73	2.58	3.41	2.50	2.70	2.91	3.37	4.51	3.00	2.62	3.07	4.01	2.43	2.74	2.16	2.78	2.97	3.16	-	-	-	-	-	-	-	
	G	-	3.15	3.21	3.07	2.69	2.69	2.61	2.94	3.06	3.15	3.00	2.59	2.85	4.71	3.35	3.40	3.39	2.41	3.16	2.97	3.68	3.76	3.50	3.64	4.27	3.34	2.90	3.66	3.38	2.87	-	-	
	H	-	3.79	4.20	4.00	3.86	4.58	4.14	3.97	3.14	4.37	3.31	3.30	2.91	4.53	2.68	2.92	2.49	2.79	2.60	3.06	3.00	3.73	3.71	4.77	3.81	3.98	4.80	3.95	4.18	-	-	-	
	I	-	3.89	4.13	3.71	3.97	3.01	3.71	3.87	4.38	3.33	2.93	5.31	4.90	4.27	3.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	A	-	1.60	1.13	1.01	1.12	1.01	1.06	1.07	1.03	1.04	0.98	0.89	1.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	B	-	1.34	1.64	1.29	1.69	1.65	1.43	1.38	2.07	1.45	1.41	0.98	0.97	1.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	VACP (3.7 m/km)	C	-	2.08	2.03	1.70	1.73	1.37	2.02	1.84	1.75	2.18	1.65	2.08	2.11	1.57	1.98	2.19	2.00	2.43	2.22	-	-	-	-	-	-	-	-	-	-	-	-	-
D		-	2.38	1.95	2.24	2.37	2.34	2.88	2.22	2.26	2.57	2.61	2.19	2.30	2.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
E		-	2.6																															

As can be seen, the five classifications were distributed vertically in the table and within each classification there are the nine runways of the airport network. Once the runways were named and ordered according to the severity of the pavement roughness, it is easy to see that as the runways are presented in each classification, the roughness severity increases. Note that in the first classification (SAYERS), pavement sections are predominantly “Very Poor” (characterized by the color red). It means that as the critical limits established by the classifications increases, the number of “red” sections decreases significantly. Table 78 allows visualizing this behavior numerically.

Table 78 Maintenance and Rehabilitation needs by IRI classification

IRI Categories	Current Classifications				Alternative Classifications					
	SAYERS		ANAC		NGPL		AVERAGE		VACP	
Very Good	0	0%	4	2%	26	15%	38	22%	30	17%
Good	4	2%	16	9%	38	22%	30	17%	43	25%
Regular	16	9%	18	10%	32	19%	37	22%	48	28%
Poor	18	10%	30	17%	27	16%	29	17%	18	10%
Very Poor	134	78%	104	60%	49	28%	38	22%	33	19%
Total	172	100%	172	100%	172	100%	172	100%	172	100%

Table 78 shows the number of pavement sections that fall into each IRI category for both current and alternative classifications, as well as the corresponding percentage compared to the 172 sections in the network. Starting with Sayer’s classification, it is easy to see that most of the airport network (78%) has a “Very Poor” condition in terms of pavement roughness. Moreover, 19% of the sections are also concentrated in the categories “Regular” and “Poor”. Although many sections can produce or generate excessive vertical accelerations or pavement load ratios due to the severity of roughness, there are also sections that are far from reaching critical limits. So, it is evident that this classification imposes an IRI limit (2.0 m/km) that misjudges the real condition of the pavement sections in terms of aircraft dynamic responses.

Conversely, the ANAC classification based on the limit of 2.5 m/km shows that the number of sections in a “Very Poor” condition decreases to 60% and that another 36% was distributed along the intermediary categories. However, there are still various sections that are being misjudged and also, the number of “Very Poor”

sections in this classification decreases only about 23% respect to the number of "Very Poor" sections in Sayer's classification. In this context, it is clear that the problem in both current classifications is that critical limits of IRI force the sections to assume an extremely bad condition when the roughness that characterizes them still does not have the capacity to negatively affect the aircraft structure and the navigation instruments, nor jeopardize the operational safety.

On the other hand, alternative classifications show to be more suitable in terms of pavement loads ratios and cockpit accelerations. As can be seen in the table, these classifications have the capability to reduce the number of "Very Poor" sections to 28% if the NGPL classification is used, to 22% with the AVERAGE classification, and to 19% with the VACP classification. It means that while the use of current classifications considers that approximately 70% of the airport network is in "Very Poor" conditions, alternative classifications allow a better selection based on excessive aircraft dynamic responses, indicating that only about 23% of the network is in "Very Poor" conditions. In other words, decision making based on alternative classifications can reduce up 67% the needs for immediate rehabilitation compared to the current classifications, what is much more likely to the condition of the pavements in the field.

6 CONCLUSIONS

The main objective of this research was to evaluate the effect of airport pavement roughness on aircraft dynamic response in terms of vertical accelerations and dynamic loads, which may compromise the aircraft safety and the pavement performance. To achieve this objective, several tasks were conducted. Firstly, current pavement roughness indices IRI and BBI were computed and then compared statistically. Secondly, aircraft dynamic responses were simulated for four representative commercial aircraft operating at several discrete operational speeds and then, correlations analyses between them were also conducted. Thirdly, IRI was correlated with aircraft dynamic responses and were conducted statistical analyses based on operational speed and aircraft weight (aircraft class). Finally, alternative classifications for airport pavement roughness evaluation were proposed based on critical aircraft dynamic responses and a case study was presented as an application example.

The main conclusions of this research are presented in the following sequence:

- 1) Comparisons between pavement roughness indices IRI and BBI;
- 2) Comparisons between vertical accelerations VACP and VACG;
- 3) Comparisons between pavement loads NGPL, MGPL, and RGPL;
- 4) Comparisons between aircraft dynamic responses and IRI;
- 5) Critical limits based on aircraft dynamic responses;
- 6) Current and alternative classifications;
- 7) Use of the ProFAA software;
- 8) Final remarks; and,
- 9) Suggestion for further studies

6.1 IRI VS. BBI

The main conclusions about the comparison between pavement roughness indices are the following:

- It was observed a strong and positive correlation between IRI and BBI for *Profile*, *Thirds*, and *Sections* samples with an average coefficient of

determination of 0.74. However, regression analysis indicates that BBI was approximately 0.10 times the IRI. This means that for a BBI value to reach or exceed the acceptable zone ($BBI \geq 1.0$) the IRI value would have to be greater than 10.0 m/km. Most of airport runways operate with roughness levels that may vary about IRI of 2.0 to 5.0 m/km because of the requirements imposed by civil aviation authorities to maintain smooth pavements. As a consequence, it is unusual that airports operate when IRI is above 5.0 m/km. Thus, if the BBI is approximately 10% of the IRI it is probable that the scale of the Boeing Bump Method needs to be evaluated and adjusted;

- Regarding to vertical accelerations at the aircraft cockpit, it was observed that maximum or peak vertical accelerations become to be critical ($>0.35\text{ g}$) when BBI is 0.20, falling into the Acceptable region of the BBI classification. In this context, there is a possibility that some pavement sections with BBI values falling into the acceptable region are subjected to excessive accelerations;

- Consequently, it is concluded that, for a first approach, the IRI can be an alternative to supports the decision-making process of an APMS. Although the IRI has been indicated to highway pavements and also its mathematical model is based on a quarter-car model that cannot be compared with the dynamic behavior of an aircraft, it has shown capable to evaluate airport pavement roughness characterized by bumps up to 100 m in length. In general, the computation of IRI for the pavement profile as a whole as well as for thirds can specifically contribute to identifying priorities at the network level of an APMS. However, for the decision-making at the project level it is strongly suggested the use of sections of 100 m in length.

6.2 VACP VS. VACG

The main conclusions about the comparison between vertical accelerations are the following:

- It was observed that vertical accelerations decrease as aircraft weight increases. However, they increase as speed increases. Vertical accelerations in the aircraft cockpit are higher than in the center of gravity, mainly between 40 to 120 knots, where variations of more than the double were found. From 140 knots,

variations between VACP and VACG were about 10% but they tended to be equal as the speed increased;

- In general, VACP and VACG exceed the critical limit of 0.40 g at 80 and 140 knots, respectively. However, vertical accelerations at the aircraft cockpit shown more sensitivity to aircraft speed than those produced at the center of gravity. In this context, aircraft Class III showed more sensibility to vertical accelerations than the others. In addition, it was observed good and positive correlations between vertical accelerations and both roughness indices (average $r=0.55$). However, BBI shows about 20% higher correlation than IRI;
- Maximum or peak vertical accelerations at the cockpit of the aircraft Class I was about twice than those in Class IV. Similarly, Maximum or peak vertical accelerations in the cockpit of the Class II result about twice than those in Class III;
- Maximum or peak vertical accelerations at the center of gravity did not vary significantly. However, Maximum vertical accelerations at the center of gravity of the aircraft Class I was almost three times than those in Class IV. Also, maximum vertical accelerations at the center of gravity of the Class II result about the Triple than those in Class III;
- It was also observed a positive and strong correlation (average $r=0.90$) between VACP and VACG in aircraft Class I vs. Class II and in Class III vs. Class IV. It means that further studies can carry out also with two aircraft classes, instead four. Thus, for example, the lightest aircraft (Class I) and heaviest aircraft (Class IV) can be chosen, reducing the amount of simulations and analyses;
- In general, it is concluded that vertical accelerations in the aircraft cockpit are more critical than those occurred at the center of gravity. Regression analysis showed that VACP are about 50% higher than VACG. Therefore, it is suggested that further studies focused principally on the aircraft cockpit.

6.3 NGPL VS. MGPL/RGPL

The main conclusions about the comparison between landing gear pavement loads are the following:

- It was observed that pavement load ratios increase as aircraft weight and speed increases, except for aircraft Class IV which was similar to Class II.

Probably, it occurred due to the aircraft size and weight as well as due to the landing gear configuration that is capable to absorb efficiently more bumps configurations than the other classes;

- At very low speeds, dynamic pavement loads at nose, main, and rear landing gears were approximately half of the maximum static pavement loads. This means that aircraft taxiing over a runway or taxiway at 20 to 40 knots are not subject to high loads that affect the landing gears and the pavement performance;
- In general, pavement load ratios at the nose landing gear shown higher than those at the main and rear landing gears. However, regression results showed that pavement load ratios at the nose gear were about 80% higher than those at the main gear, except for the aircraft Class I where, contrary, MGPL was about 137% higher than NGPL. Additionally, it was observed very low and positive correlation between pavement load ratios and both roughness indices, principally with MGPL and RGPL (average $r=0.065$). Even so, BBI shows about 75% higher correlation with pavement loads than IRI;
- It was observed that aircraft Class I and II has strong correlation ($r=0.94$) only between MGPL. Conversely, aircraft class III and IV has strong correlation (average $r=0.77$) with NGPL, MGPL, and RGPL;
- Finally, MGPL was approximately 3% higher than RGPL in aircraft Class IV. However, since there was no significant variation, they can be assumed equal in further studies.

6.4 AIRCRAFT DYNAMIC RESPONSES VS. IRI

The main conclusions about the comparison between aircraft dynamic responses and IRI are the following:

- It was observed that vertical accelerations at the aircraft cockpit increase at a rate of 20 to 60% as the IRI increases. Furthermore, although vertical accelerations at the center of gravity were less than those in the cockpit, they increased at a rate of 20 to 90% as the IRI increases. Thus, as the pavement deteriorate, not only the accelerations increase but also the dispersion between them increases and at a significant rate;
- Vertical accelerations higher than 0.40 g represents less than 1% of the values in the database ($n=22,800$) and they occurred between IRI 1.6 and

2.5 m/km. Therefore, caution is needed when the IRI falls between these values since eventually peak accelerations can occur;

- Pavement loads ratios above 1.5 were found mainly when IRI is between 1.8 and 2.6 m/km. So, similarly to vertical accelerations, caution is needed when the IRI falls between these values since eventually high loads can occur;
- At 60 and 80 knots and IRI between 1.5 and 2.0 m/km, maximum NGPL in class III can be as high as 0.80 and also can exceed 1.0 when roughness is above 2.5 m/km;
- In general, aircraft Class III showed high sensitivity to pavement roughness in terms of pavement loads respect to the others classes;
- Finally, it is suggested that further studies focuses, mainly, on the study of vertical accelerations at the aircraft cockpit and pavement loads at the nose landing gear.

6.5 CRITICAL LIMITS BASED ON AIRCRAFT DYNAMIC RESPONSES

The main conclusions about critical limits resulting from regression analyses are the following:

- All the regression models presented in this research to identify critical limits for pavement roughness indices were significant ($P\text{-value} < 0.05$) and indicate very strong and positive coefficient of determination (average $r=0.85$). Furthermore, the scatterplots of standardized predicted values versus standardized residuals showed that the data met the assumptions of homogeneity of variance and linearity of the residuals were normally distributed. This means that the transformation method used allows improving data normality and, therefore, is recommended in further studies;
- According with the regression analyses, critical models characterized by excessive vertical accelerations and high dynamic load ratios were identified for the variables VACP and NGPL;
- In this context, it was observed that vertical accelerations at the aircraft cockpit become to be critical ($>0.35\text{ g}$) when IRI is 3.4 m/km and when BBI is 0.20; and exceeds the critical limit of 0.40 g when they are above 3.7 m/km and 0.20, respectively. On the other hand, vertical accelerations at the center of

gravity become to be critical only when IRI is 4.7 m/km and when BBI is 0.30; and exceeds the critical limit when they are above 5.1 m/km and 0.30, respectively. Consequently, it is evident that the most critical model was VACP;

- Similarly, it was observed that pavement load ratios at the nose landing gear become to be high (>1.5) when IRI is 2.9 m/km and when the BBI is 0.40; and are twice the static load when they are above 3.3 m/km and 0.50, respectively. On the other hand, pavement load ratios at the main landing gear become to be critical only when IRI is 3.5 m/km and when BBI is 0.60; and are twice the static load when they are above 4.0 m/km and 0.70, respectively. Finally, pavement load ratios at the rear landing gear become to be critical only when IRI is 3.6 m/km and when BBI is 0.60; and are twice the static load when they are above 4.1 m/km and 0.80, respectively. Consequently, it is evident that the most critical model was NGPL;

- As a consequence, it is concluded that further studies should be focus principally on the vertical accelerations occurred at the aircraft cockpit and the pavement loads imposed by the nose landing gear.

6.6 AIRPORT PAVEMENT ROUGHNESS CLASSIFICATIONS

Three alternative classifications for IRI based on aircraft dynamic responses were proposed. Each one was based on the critical limits for NGPL (3.3 m/km), for the average between NGPL and VACP (3.5 m/km), and for VACP (3.7 m/km). Furthermore, two additional classifications were also proposed based on the current limits suggested by Sayers & Karamihas (1998) – 2.0 m/km – and established by ANAC (2019) – 2.5 m/km, in order to serves as a reference for the case study presented in this research. The main conclusions about these classifications are the following:

- Accordingly with the case study, it was observed that when the critical limit of IRI is 2.0 m/km (Sayer's classification), 78% of the pavements sections in the airport network have a "Very Poor" condition in terms of pavement roughness and another 19% fallen into the categories "Regular" and "Poor". However, most of these sections are far from reaching excessive vertical accelerations and high pavement loads ratios. So, it is evident that the IRI limit of 2.0 m/km misjudges the real condition of the pavement sections in terms of aircraft dynamic responses;

- The same occurred when the critical limit of IRI was 2.5 m/km (ANAC classification). Here, the number of sections in a “Very Poor” condition decreased by 60% and another 36% was distributed into the intermediary categories. However, it was observed that the condition of various sections is being also overestimated. In general, the number of “Very Poor” sections in this classification decreases only about 23% respect to the Sayer’s classification;

- In this context, the problem in both of these classifications is that current critical IRI limits force the sections to assume an extremely bad condition when the pavement roughness still does not have the severity to negatively affect the aircraft structure and/or the navigation instruments, nor jeopardize the operational safety;

- Conversely, alternative classifications shown to be more suitable in terms of pavement loads ratios and cockpit accelerations than the others above. With the use of the NGPL classification, for example, it was observed a reduction of 28% in the number of “Very Poor” sections. In the same way, with the use of the AVERAGE and VACP classifications it was observed a reduction of 22% and 19% in the number of sections in a “Very Poor” condition, respectively. In other words, while Sayer’s and ANAC classifications assume that about 70% of the airport network needs to be rehabilitated, alternative classifications provide a better selection based on excessive aircraft dynamic responses where only approximately 23% needs this kind of treatment. Thus, for the case study presented in this research, decision making based on alternative classifications reduced to 67% the needs for immediate rehabilitation compared to the current classifications;

- So, it is evident that alternative classifications can help airport managers and engineers to make decisions based on additional criteria, such as aircraft dynamic responses, mainly because the alternative classifications are much more representative of the condition observed in the field;

- Consequently, it is recommended the use of alternative classifications in airport pavements in order to reduce the number of unnecessary maintenance and rehabilitation treatments. As a first approach in an airport pavement roughness evaluation through aircraft dynamic responses it is suggested the use of the AVERAGE classification based on VACP and NGPL (Table 65). However,

the use and results interpretation by the use of any classification (current or alternative) presented in this research is the responsibility of the user. In addition, as discussed above, the choice of the best or ideal classifications will depend directly on the technical needs of a specific airport network or runway as well as on the priorities established by airport managers, engineers, and those involved in the decision-making process. Finally, it is extremely important to keep in mind that the use of any of these alternative classifications should be accompanied by the evaluation of the pavement elevation profile and that simulations of dynamic responses by ProFAA software also should be carried out.

6.7 CONCLUSIONS ABOUT THE PROFAA SOFTWARE

ProFAA is a Visual Basic (VB6) program developed by the Federal Aviation Administration to assess, officially and free, airport pavement roughness. The use of the software in this research provided information related to ride quality and potential aircraft structural damage in terms of pavement roughness indices and aircraft dynamic response. The principal software advantage is the capability to compute IRI and BBI as well as to simulate vertical accelerations and dynamic loads in a low-time consuming computational process. However, there is an important disadvantage related to the source code. Although the user has access to the program code for local modifications, it was perceived that most of the variables are not totally described and the names of them are confusing, consequently, the user is unable to make modifications. Thus, there is a need for a user's manual addressing this issue.

It is important to note that the software is constantly updated and that new and/or trial versions may be launched. Consequently, depending on the version used there may be some variations in the results, principally in aircraft simulations. This is probably due to the 10-year Research & Development Program that is being implemented by the FAA (see Figure 18) and that may result in program code modifications and unexpected updates. Nevertheless, the current software package is available for free and can be downloaded from <http://www.airporttech.tc.faa.gov>. The version used in this research was launched on July 27, 2017.

It is encouraged the use of the ProFAA software to assess the pavement roughness of any airport network or runway. The software allows airport managers

and engineers to identifying critical sections from a different point of view, based now on the effect of aircraft dynamic responses. Furthermore, this software can contribute to improve an Airport Pavement Management System and supports the decision-making process. Nevertheless, meanwhile, it is suggested the use of alternate classifications, but for a short time (network level)

6.8 FINAL REMARKS

One of the main challenges to carry out this research was the difficulty in acquiring pavement elevation profiles. Nowadays, pavement roughness information can be a confidential issue for many airport authorities, probably because of the amount and type of information provided by the analysis of an elevation profile, related to safety and quality of ground operations. Furthermore, many companies that offer roughness measurements services, provides technical reports containing only results in terms of IRI or another pavement roughness index, despising elevation profile data.

As discussed previously, the pavement elevation profiles used in this research correspond to real-world runways, but were acquired from a FAA database. This was due to the delay and bureaucracy to acquire any type of information about runways quality and mainly because many airport authorities were not aware of what an elevation profile was and because they do not required this type of information from the companies they hired to perform the measurements.

Thus, this research serves as an example to show the importance of the analysis of the elevation profile for airport pavement roughness assessment. Elevation profiles allow computing any pavement roughness index, identifying and studying critical sections, and simulating aircraft dynamic responses. Moreover, a pavement elevation profile also allows establishing a variety of IRI classifications or criteria based on excessive vertical accelerations and high dynamic loads, as it performed in this research, which would significantly reduce the number of unnecessary pavement rehabilitation activities.

6.9 SUGGESTIONS FOR FURTHER STUDIES

The following suggestions for future studies are presented:

- To build or generate “artificial” pavement elevation profiles for a variety of bump configurations with different bump lengths and heights. A perfectly-smooth artificial pavement profile (without elevation changes) can be used as a reference. Analysis of artificial profiles can contribute to identifying significant roughness patterns and specific bump configurations which can be responsible for excessive aircraft dynamic responses;
- To carry out subjective studies in order to assess pavement roughness through pilot’s perception. It is extremely important to study the elevation profile of an airport pavement network or runway where there is access to the pilot’s complaints database and where there is the possibility of carrying out a subjective evaluation in the form of questionnaires distributed to commercial aircraft pilots operating in such network or runway. Annex C presents the questionnaire proposed by Horn (1977) as an example;
- To modify the ProFAA source code in order to carry out simulations based on an alternative aircraft library;
- To perform factorial analysis based on multivariate models that take into account the variables together;
- To perform economic analysis for the alternative IRI classifications proposed in this research.

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APPENDIX A – AIRPORT PAVEMENT ELEVATION PROFILES

APPENDIX B – PAVEMENT ROUGHNESS INDICES

IRI and BBI for “Very Good” pavement elevation profiles.

Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI
1	Very_Good	3048	0	100	0,20	0,0164	3	Very_Good	1473	0	100	0,90	0,3915
1	Very_Good	3048	100	200	0,20	0,0151	3	Very_Good	1473	100	200	0,90	0,1883
1	Very_Good	3048	200	300	0,20	0,0192	3	Very_Good	1473	200	300	0,80	0,2121
1	Very_Good	3048	300	400	0,20	0,0373	3	Very_Good	1473	300	400	0,90	0,3554
1	Very_Good	3048	400	500	0,30	0,0198	3	Very_Good	1473	400	500	1,00	0,1604
1	Very_Good	3048	500	600	0,20	0,0221	3	Very_Good	1473	500	600	0,90	0,1569
1	Very_Good	3048	600	700	0,20	0,0319	3	Very_Good	1473	600	700	0,60	0,1488
1	Very_Good	3048	700	800	0,20	0,0414	3	Very_Good	1473	700	800	0,70	0,0930
1	Very_Good	3048	800	900	0,20	0,0200	3	Very_Good	1473	800	900	0,80	0,0759
1	Very_Good	3048	900	1000	0,20	0,0144	3	Very_Good	1473	900	1000	0,70	0,0761
1	Very_Good	3048	1000	1100	0,20	0,0113	3	Very_Good	1473	1000	1100	0,60	0,1727
1	Very_Good	3048	1100	1200	0,20	0,0191	3	Very_Good	1473	1100	1200	0,50	0,1569
1	Very_Good	3048	1200	1300	0,20	0,0178	3	Very_Good	1473	1200	1300	0,60	0,2441
1	Very_Good	3048	1300	1400	0,20	0,0142	3	Very_Good	1473	1300	1400	0,50	0,3713
1	Very_Good	3048	1400	1500	0,20	0,0125	3	Very_Good	1473	1400	1473	1,10	0,2389
1	Very_Good	3048	1500	1600	0,20	0,0156							
1	Very_Good	3048	1600	1700	0,20	0,0159							
1	Very_Good	3048	1700	1800	0,20	0,0178							
1	Very_Good	3048	1800	1900	0,20	0,0155							
1	Very_Good	3048	1900	2000	0,20	0,0155							
1	Very_Good	3048	2000	2100	0,20	0,0150							
1	Very_Good	3048	2100	2200	0,20	0,0135							
1	Very_Good	3048	2200	2300	0,20	0,0246							
1	Very_Good	3048	2300	2400	0,20	0,0252							
1	Very_Good	3048	2400	2500	0,30	0,0183							
1	Very_Good	3048	2500	2600	0,20	0,0324							
1	Very_Good	3048	2600	2700	0,20	0,0194							
1	Very_Good	3048	2700	2800	0,10	0,0107							
1	Very_Good	3048	2800	2900	0,20	0,0157							
1	Very_Good	3048	2900	3000	0,20	0,0186							
1	Very_Good	3048	3000	3048	0,20	0,0144							
2	Very_Good	2523	0	100	0,70	0,2178							
2	Very_Good	2523	100	200	0,40	0,0938							
2	Very_Good	2523	200	300	0,40	0,0861							
2	Very_Good	2523	300	400	0,60	0,0957							
2	Very_Good	2523	400	500	0,50	0,0821							
2	Very_Good	2523	500	600	0,40	0,0835							
2	Very_Good	2523	600	700	0,50	0,1089							
2	Very_Good	2523	700	800	0,50	0,1212							
2	Very_Good	2523	800	900	0,40	0,1013							
2	Very_Good	2523	900	1000	0,60	0,1069							
2	Very_Good	2523	1000	1100	0,50	0,0642							
2	Very_Good	2523	1100	1200	0,70	0,0765							
2	Very_Good	2523	1200	1300	0,60	0,0894							
2	Very_Good	2523	1300	1400	0,50	0,0844							
2	Very_Good	2523	1400	1500	0,60	0,0928							
2	Very_Good	2523	1500	1600	0,50	0,0822							
2	Very_Good	2523	1600	1700	0,60	0,0767							
2	Very_Good	2523	1700	1800	0,60	0,0891							
2	Very_Good	2523	1800	1900	0,50	0,1003							
2	Very_Good	2523	1900	2000	0,80	0,1442							
2	Very_Good	2523	2000	2100	0,80	0,1023							
2	Very_Good	2523	2100	2200	0,60	0,0808							
2	Very_Good	2523	2200	2300	0,60	0,1434							
2	Very_Good	2523	2300	2400	0,50	0,1054							
2	Very_Good	2523	2400	2500	0,40	0,0938							
2	Very_Good	2523	2500	2523	0,70	0,1866							

IRI and BBI for “Good” pavement elevation profiles

Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI
4	Good	1760	0	100	1,3	0,1923	7	Good	2781	0	100	1,5	0,1977	9	Good	3680	100	200	1,50	0,1802
4	Good	1760	100	200	0,9	0,1282	7	Good	2781	100	200	0,9	0,0888	9	Good	3680	200	300	1,10	0,1005
4	Good	1760	200	300	1,0	0,1142	7	Good	2781	200	300	0,9	0,0921	9	Good	3680	300	400	1,50	0,1841
4	Good	1760	300	400	1,3	0,2162	7	Good	2781	300	400	0,9	0,1052	9	Good	3680	400	500	1,50	0,1452
4	Good	1760	400	500	1,2	0,1349	7	Good	2781	400	500	1,4	0,1583	9	Good	3680	500	600	1,10	0,0946
4	Good	1760	500	600	0,8	0,0980	7	Good	2781	500	600	1,1	0,1724	9	Good	3680	600	700	1,60	0,1706
4	Good	1760	600	700	1,1	0,1295	7	Good	2781	600	700	1,1	0,1056	9	Good	3680	700	800	1,50	0,1132
4	Good	1760	700	800	0,9	0,1351	7	Good	2781	700	800	1,2	0,1164	9	Good	3680	800	900	1,30	0,1609
4	Good	1760	800	900	1,2	0,1641	7	Good	2781	800	900	1,2	0,1074	9	Good	3680	900	1000	1,40	0,2086
4	Good	1760	900	1000	1,0	0,1390	7	Good	2781	900	1000	1,6	0,1574	9	Good	3680	1000	1100	1,80	0,3426
4	Good	1760	1000	1100	1,0	0,1851	7	Good	2781	1000	1100	1,3	0,1753	9	Good	3680	1100	1200	1,70	0,2551
4	Good	1760	1100	1200	0,7	0,1173	7	Good	2781	1100	1200	1,2	0,1461	9	Good	3680	1200	1300	1,40	0,1819
4	Good	1760	1200	1300	0,8	0,0874	7	Good	2781	1200	1300	1,3	0,1604	9	Good	3680	1300	1400	1,40	0,1247
4	Good	1760	1300	1400	1,0	0,1355	7	Good	2781	1300	1400	1,3	0,1199	9	Good	3680	1400	1500	1,40	0,1304
4	Good	1760	1400	1500	0,8	0,0983	7	Good	2781	1400	1500	1,5	0,1503	9	Good	3680	1500	1600	1,40	0,1563
4	Good	1760	1500	1600	1,2	0,1397	7	Good	2781	1500	1600	1,1	0,1252	9	Good	3680	1600	1700	1,20	0,1519
4	Good	1760	1600	1700	0,9	0,0856	7	Good	2781	1600	1700	0,9	0,1375	9	Good	3680	1700	1800	1,70	0,1545
4	Good	1760	1700	1760	0,9	0,1191	7	Good	2781	1700	1800	1,2	0,1103	9	Good	3680	1800	1900	1,60	0,1580
5	Good	3161	0	100	1,4	0,1790	7	Good	2781	1800	1900	1,2	0,1243	9	Good	3680	1900	2000	1,30	0,1543
5	Good	3161	100	200	1,3	0,1286	7	Good	2781	1900	2000	1,1	0,1045	9	Good	3680	2000	2100	1,10	0,1237
5	Good	3161	200	300	1,2	0,1130	7	Good	2781	2000	2100	1,2	0,1250	9	Good	3680	2100	2200	1,10	0,2009
5	Good	3161	300	400	1,0	0,1031	7	Good	2781	2100	2200	1,1	0,1458	9	Good	3680	2200	2300	1,10	0,1280
5	Good	3161	400	500	1,0	0,1076	7	Good	2781	2200	2300	1,1	0,1054	9	Good	3680	2300	2400	1,10	0,0954
5	Good	3161	500	600	0,9	0,0718	7	Good	2781	2300	2400	1,4	0,1277	9	Good	3680	2400	2500	1,40	0,2587
5	Good	3161	600	700	0,9	0,0945	7	Good	2781	2400	2500	1,2	0,1088	9	Good	3680	2500	2600	1,50	0,2115
5	Good	3161	700	800	0,9	0,0751	7	Good	2781	2500	2600	1,0	0,0883	9	Good	3680	2600	2700	1,50	0,1693
5	Good	3161	800	900	1,1	0,1095	7	Good	2781	2600	2700	1,0	0,1095	9	Good	3680	2700	2800	1,40	0,1441
5	Good	3161	900	1000	0,8	0,0996	7	Good	2781	2700	2781	1,2	0,1901	9	Good	3680	2800	2900	1,30	0,2667
5	Good	3161	1000	1100	1,0	0,0943	8	Good	3877	0	100	1,2	0,1091	9	Good	3680	2900	3000	1,40	0,2106
5	Good	3161	1100	1200	0,9	0,0855	8	Good	3877	100	200	1,5	0,1064	9	Good	3680	3000	3100	1,10	0,1882
5	Good	3161	1200	1300	0,8	0,0762	8	Good	3877	200	300	1,8	0,1312	9	Good	3680	3100	3200	1,20	0,1239
5	Good	3161	1300	1400	1,0	0,0898	8	Good	3877	300	400	2,0	0,1312	9	Good	3680	3200	3300	1,20	0,1394
5	Good	3161	1400	1500	1,0	0,1128	8	Good	3877	400	500	1,6	0,1258	9	Good	3680	3300	3400	1,30	0,1129
5	Good	3161	1500	1600	0,8	0,0749	8	Good	3877	500	600	1,6	0,1784	9	Good	3680	3400	3500	1,10	0,1115
5	Good	3161	1600	1700	1,1	0,1174	8	Good	3877	600	700	1,1	0,1097	9	Good	3680	3500	3600	1,10	0,2675
5	Good	3161	1700	1800	1,1	0,0866	8	Good	3877	700	800	1,2	0,1293							
5	Good	3161	1800	1900	0,9	0,0751	8	Good	3877	800	900	1,1	0,1119							
5	Good	3161	1900	2000	1,2	0,0983	8	Good	3877	900	1000	1,1	0,0854							
5	Good	3161	2000	2100	1,3	0,1102	8	Good	3877	1000	1100	1,3	0,1135							
5	Good	3161	2100	2200	1,3	0,1199	8	Good	3877	1100	1200	1,1	0,0964							
5	Good	3161	2200	2300	1,1	0,0947	8	Good	3877	1200	1300	1,1	0,0972							
5	Good	3161	2300	2400	1,0	0,0840	8	Good	3877	1300	1400	1,2	0,1203							
5	Good	3161	2400	2500	1,0	0,0988	8	Good	3877	1400	1500	1,4	0,1603							
5	Good	3161	2500	2600	0,7	0,0739	8	Good	3877	1500	1600	1,6	0,1926							
5	Good	3161	2600	2700	0,8	0,0646	8	Good	3877	1600	1700	1,7	0,1658							
5	Good	3161	2700	2800	0,9	0,0939	8	Good	3877	1700	1800	1,4	0,1535							
5	Good	3161	2800	2900	0,8	0,0946	8	Good	3877	1800	1900	1,5	0,2317							
5	Good	3161	2900	3000	0,8	0,0734	8	Good	3877	1900	2000	1,3	0,1145							
5	Good	3161	3000	3100	0,8	0,0888	8	Good	3877	2000	2100	1,5	0,1272							
5	Good	3161	3100	3161	0,8	0,1546	8	Good	3877	2100	2200	1,5	0,1489							
6	Good	1761	0	100	1,2	0,1893	8	Good	3877	2200	2300	1,2	0,0862							
6	Good	1761	100	200	0,7	0,0732	8	Good	3877	2300	2400	0,8	0,0888							
6	Good	1761	200	300	0,9	0,1285	8	Good	3877	2400	2500	1,0	0,0924							
6	Good	1761	300	400	1,0	0,1590	8	Good	3877	2500	2600	0,9	0,0754							
6	Good	1761	400	500	1,0	0,1297	8	Good	3877	2600	2700	1,5	0,1544							
6	Good	1761	500	600	1,2	0,1267	8	Good	3877	2700	2800	1,1	0,0974							
6	Good	1761	600	700	1,0	0,1595	8	Good	3877	2800	2900	1,0	0,0912							
6	Good	1761	700	800	1,5	0,1745	8	Good	3877	2900	3000	1,0	0,0928							
6	Good	1761	800	900	1,0	0,1179	8	Good	3877	3000	3100	1,1	0,0943							
6	Good	1761	900	1000	0,9	0,0926	8	Good	3877	3100	3200	1,1	0,0846							
6	Good	1761	1000	1100	1,1	0,1387	8	Good	3877	3200	3300	1,3	0,1061							
6	Good	1761	1100	1200	0,9	0,0877	8	Good	3877	3300	3400	1,0	0,0921							
6	Good	1761	1200	1300	1,1	0,1080	8	Good	3877	3400	3500	1,1	0,1110							
6	Good	1761	1300	1400	1,1	0,1422	8	Good	3877	3500	3600	1,1	0,0924							
6	Good	1761	1400	1500	1,2	0,1706	8	Good	3877	3600	3700	1,4	0,1260							
6	Good	1761	1500	1600	0,8	0,1146	8	Good	3877	3700	3800	1,1	0,1555							
6	Good	1761	1600	1700	1,1	0,0855	8	Good	3877	3800	3877	1,1	0,1725							
6	Good	1761	1700	1761	1,4	0,1504	9	Good	3680	0	100	1,6	0,1495							

IRI and BBI for “Regular” pavement elevation profiles

Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI
10	Regular	3174	0	100	1,6	0,2291	12	Regular	3104	0	100	1,9	0,2366
10	Regular	3174	100	200	1,4	0,1309	12	Regular	3104	100	200	1,5	0,2371
10	Regular	3174	200	300	1,2	0,0912	12	Regular	3104	200	300	1,6	0,2563
10	Regular	3174	300	400	1,2	0,1076	12	Regular	3104	300	400	1,7	0,2218
10	Regular	3174	400	500	1,2	0,1130	12	Regular	3104	400	500	1,8	0,2767
10	Regular	3174	500	600	1,8	0,1653	12	Regular	3104	500	600	1,9	0,2039
10	Regular	3174	600	700	1,7	0,1766	12	Regular	3104	600	700	1,4	0,2700
10	Regular	3174	700	800	1,4	0,1243	12	Regular	3104	700	800	1,6	0,1876
10	Regular	3174	800	900	1,3	0,1231	12	Regular	3104	800	900	1,7	0,2558
10	Regular	3174	900	1000	1,5	0,1144	12	Regular	3104	900	1000	1,3	0,1283
10	Regular	3174	1000	1100	1,4	0,1135	12	Regular	3104	1000	1100	1,5	0,1524
10	Regular	3174	1100	1200	1,6	0,1409	12	Regular	3104	1100	1200	1,9	0,1991
10	Regular	3174	1200	1300	1,4	0,1071	12	Regular	3104	1200	1300	1,7	0,1939
10	Regular	3174	1300	1400	1,2	0,1006	12	Regular	3104	1300	1400	1,5	0,2530
10	Regular	3174	1400	1500	1,3	0,1076	12	Regular	3104	1400	1500	1,6	0,1721
10	Regular	3174	1500	1600	1,9	0,1780	12	Regular	3104	1500	1600	1,7	0,2024
10	Regular	3174	1600	1700	1,7	0,1447	12	Regular	3104	1600	1700	1,3	0,1954
10	Regular	3174	1700	1800	1,6	0,1070	12	Regular	3104	1700	1800	1,4	0,2462
10	Regular	3174	1800	1900	1,5	0,1017	12	Regular	3104	1800	1900	1,6	0,1609
10	Regular	3174	1900	2000	1,7	0,1141	12	Regular	3104	1900	2000	1,6	0,2823
10	Regular	3174	2000	2100	1,3	0,1266	12	Regular	3104	2000	2100	2,7	0,3003
10	Regular	3174	2100	2200	1,8	0,2111	12	Regular	3104	2100	2200	2,6	0,2739
10	Regular	3174	2200	2300	1,7	0,1930	12	Regular	3104	2200	2300	1,9	0,1989
10	Regular	3174	2300	2400	1,5	0,1049	12	Regular	3104	2300	2400	1,4	0,1969
10	Regular	3174	2400	2500	1,6	0,1173	12	Regular	3104	2400	2500	2,4	0,2730
10	Regular	3174	2500	2600	1,5	0,1279	12	Regular	3104	2500	2600	2,6	0,2455
10	Regular	3174	2600	2700	1,9	0,1699	12	Regular	3104	2600	2700	2,4	0,3697
10	Regular	3174	2700	2800	2,0	0,1209	12	Regular	3104	2700	2800	1,8	0,5751
10	Regular	3174	2800	2900	1,9	0,1580	12	Regular	3104	2800	2900	2,1	0,4002
10	Regular	3174	2900	3000	1,6	0,1256	12	Regular	3104	2900	3000	1,5	0,1689
10	Regular	3174	3000	3100	1,6	0,1439	12	Regular	3104	3000	3104	2,3	0,2209
10	Regular	3174	3100	3174	1,8	0,2638							
11	Regular	3178	0	100	1,8	0,2955							
11	Regular	3178	100	200	1,6	0,1697							
11	Regular	3178	200	300	1,9	0,1899							
11	Regular	3178	300	400	1,5	0,1755							
11	Regular	3178	400	500	1,7	0,1293							
11	Regular	3178	500	600	1,7	0,1493							
11	Regular	3178	600	700	2,3	0,2129							
11	Regular	3178	700	800	2,1	0,1686							
11	Regular	3178	800	900	2,1	0,2035							
11	Regular	3178	900	1000	1,7	0,1630							
11	Regular	3178	1000	1100	1,7	0,2174							
11	Regular	3178	1100	1200	1,3	0,1595							
11	Regular	3178	1200	1300	1,4	0,1526							
11	Regular	3178	1300	1400	1,3	0,1351							
11	Regular	3178	1400	1500	1,0	0,1153							
11	Regular	3178	1500	1600	1,5	0,2051							
11	Regular	3178	1600	1700	1,3	0,1528							
11	Regular	3178	1700	1800	1,3	0,1494							
11	Regular	3178	1800	1900	1,6	0,2488							
11	Regular	3178	1900	2000	1,5	0,1726							
11	Regular	3178	2000	2100	1,2	0,1441							
11	Regular	3178	2100	2200	1,4	0,2477							
11	Regular	3178	2200	2300	1,5	0,2155							
11	Regular	3178	2300	2400	1,8	0,3500							
11	Regular	3178	2400	2500	1,6	0,3237							
11	Regular	3178	2500	2600	1,8	0,2201							
11	Regular	3178	2600	2700	1,4	0,1520							
11	Regular	3178	2700	2800	1,4	0,1912							
11	Regular	3178	2800	2900	1,8	0,2023							
11	Regular	3178	2900	3000	1,5	0,1983							
11	Regular	3178	3000	3100	1,6	0,3593							
11	Regular	3178	3100	3178	1,4	0,2895							

IRI and BBI for “Poor” pavement elevation profiles

Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI
13	Poor	3768	0	100	2,4	0,2179	15	Poor	2724	0	100	2,2	0,2054
13	Poor	3768	100	200	2,6	0,1908	15	Poor	2724	100	200	1,6	0,1655
13	Poor	3768	200	300	1,9	0,1307	15	Poor	2724	200	300	2,5	0,2236
13	Poor	3768	300	400	2,1	0,1719	15	Poor	2724	300	400	2,0	0,1838
13	Poor	3768	400	500	2,0	0,1572	15	Poor	2724	400	500	2,0	0,1779
13	Poor	3768	500	600	1,9	0,1397	15	Poor	2724	500	600	2,0	0,3429
13	Poor	3768	600	700	2,1	0,1672	15	Poor	2724	600	700	2,2	0,1958
13	Poor	3768	700	800	2,1	0,1764	15	Poor	2724	700	800	2,1	0,2152
13	Poor	3768	800	900	1,8	0,1411	15	Poor	2724	800	900	1,9	0,1884
13	Poor	3768	900	1000	2,0	0,1441	15	Poor	2724	900	1000	3,2	0,2735
13	Poor	3768	1000	1100	2,1	0,1571	15	Poor	2724	1000	1100	3,1	0,3281
13	Poor	3768	1100	1200	2,3	0,2201	15	Poor	2724	1100	1200	2,4	0,2132
13	Poor	3768	1200	1300	2,3	0,1833	15	Poor	2724	1200	1300	2,8	0,2201
13	Poor	3768	1300	1400	2,0	0,1966	15	Poor	2724	1300	1400	2,1	0,1691
13	Poor	3768	1400	1500	2,0	0,1449	15	Poor	2724	1400	1500	2,3	0,2106
13	Poor	3768	1500	1600	1,7	0,1482	15	Poor	2724	1500	1600	2,2	0,2415
13	Poor	3768	1600	1700	2,4	0,1983	15	Poor	2724	1600	1700	2,8	0,2561
13	Poor	3768	1700	1800	2,2	0,1519	15	Poor	2724	1700	1800	2,0	0,2168
13	Poor	3768	1800	1900	1,8	0,1387	15	Poor	2724	1800	1900	1,6	0,1218
13	Poor	3768	1900	2000	2,0	0,1538	15	Poor	2724	1900	2000	1,8	0,1405
13	Poor	3768	2000	2100	2,1	0,1958	15	Poor	2724	2000	2100	1,8	0,1890
13	Poor	3768	2100	2200	1,9	0,1358	15	Poor	2724	2100	2200	1,9	0,1997
13	Poor	3768	2200	2300	1,8	0,1137	15	Poor	2724	2200	2300	2,2	0,2827
13	Poor	3768	2300	2400	1,7	0,1336	15	Poor	2724	2300	2400	3,1	0,2225
13	Poor	3768	2400	2500	1,9	0,1582	15	Poor	2724	2400	2500	2,4	0,2364
13	Poor	3768	2500	2600	2,0	0,1604	15	Poor	2724	2500	2600	2,4	0,2044
13	Poor	3768	2600	2700	1,9	0,1475	15	Poor	2724	2600	2700	2,3	0,1858
13	Poor	3768	2700	2800	1,7	0,1471	15	Poor	2724	2700	2724	2,0	0,1282
13	Poor	3768	2800	2900	1,5	0,1377	16	Poor	2207	0	100	2,5	0,6823
13	Poor	3768	2900	3000	2,4	0,1767	16	Poor	2207	100	200	2,1	0,5308
13	Poor	3768	3000	3100	2,3	0,1653	16	Poor	2207	200	300	2,2	0,2236
13	Poor	3768	3100	3200	2,4	0,1678	16	Poor	2207	300	400	2,3	0,2480
13	Poor	3768	3200	3300	2,4	0,1499	16	Poor	2207	400	500	2,2	0,5451
13	Poor	3768	3300	3400	2,0	0,1621	16	Poor	2207	500	600	2,3	0,2289
13	Poor	3768	3400	3500	2,3	0,1857	16	Poor	2207	600	700	2,5	0,2262
13	Poor	3768	3500	3600	2,4	0,1782	16	Poor	2207	700	800	2,2	0,3404
13	Poor	3768	3600	3700	2,2	0,1856	16	Poor	2207	800	900	2,4	0,2175
13	Poor	3768	3700	3768	2,6	0,4385	16	Poor	2207	900	1000	2,1	0,2206
14	Poor	2726	100	200	1,9	0,3505	16	Poor	2207	1000	1100	2,7	0,2938
14	Poor	2726	200	300	2,1	0,3595	16	Poor	2207	1100	1200	2,4	0,2058
14	Poor	2726	300	400	2,1	0,2017	16	Poor	2207	1200	1300	2,2	0,2292
14	Poor	2726	400	500	2,3	0,2518	16	Poor	2207	1300	1400	2,1	0,1915
14	Poor	2726	500	600	2,1	0,3349	16	Poor	2207	1400	1500	2,3	0,2183
14	Poor	2726	600	700	1,6	0,2568	16	Poor	2207	1500	1600	1,9	0,1778
14	Poor	2726	700	800	1,6	0,3481	16	Poor	2207	1600	1700	2,3	0,2193
14	Poor	2726	800	900	1,8	0,2701	16	Poor	2207	1700	1800	1,8	0,2623
14	Poor	2726	900	1000	3,2	0,5366	16	Poor	2207	1800	1900	2,3	0,3411
14	Poor	2726	1000	1100	2,5	0,2720	16	Poor	2207	1900	2000	1,8	0,2199
14	Poor	2726	1100	1200	2,5	0,2052	16	Poor	2207	2000	2100	2,3	0,2839
14	Poor	2726	1200	1300	2,0	0,2192	16	Poor	2207	2100	2207	3,7	0,3009
14	Poor	2726	1300	1400	2,3	0,2477							
14	Poor	2726	1400	1500	1,8	0,2145							
14	Poor	2726	1500	1600	2,3	0,1825							
14	Poor	2726	1600	1700	1,7	0,2052							
14	Poor	2726	1700	1800	1,6	0,2122							
14	Poor	2726	1800	1900	1,7	0,2160							
14	Poor	2726	1900	2000	1,8	0,1628							
14	Poor	2726	2000	2100	1,5	0,1463							
14	Poor	2726	2100	2200	1,9	0,2678							
14	Poor	2726	2200	2300	2,0	0,2679							
14	Poor	2726	2300	2400	1,7	0,2809							
14	Poor	2726	2400	2500	2,4	0,2196							
14	Poor	2726	2500	2600	2,5	0,2238							
14	Poor	2726	2600	2700	2,0	0,2022							
14	Poor	2726	2700	2726	3,3	0,5950							

IRI and BBI for “Very Poor” pavement elevation profiles

Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI	Profile	RATING	LENGTH	STARTS	ENDS	IRI	BBI
17	Very_Poor	3658	0	100	2,8	0,1969	19	Very_Poor	3371	0	100	3,1	0,2441
17	Very_Poor	3658	100	200	2,3	0,1806	19	Very_Poor	3371	100	200	3,1	0,2034
17	Very_Poor	3658	200	300	2,2	0,2300	19	Very_Poor	3371	200	300	2,4	0,1518
17	Very_Poor	3658	300	400	2,6	0,4473	19	Very_Poor	3371	300	400	2,2	0,1383
17	Very_Poor	3658	400	500	3,1	0,2373	19	Very_Poor	3371	400	500	2,5	0,1763
17	Very_Poor	3658	500	600	2,8	0,2656	19	Very_Poor	3371	500	600	2,5	0,1892
17	Very_Poor	3658	600	700	1,9	0,3831	19	Very_Poor	3371	600	700	2,4	0,1620
17	Very_Poor	3658	700	800	2,7	0,4965	19	Very_Poor	3371	700	800	2,6	0,1678
17	Very_Poor	3658	800	900	2,6	0,2399	19	Very_Poor	3371	800	900	2,6	0,1747
17	Very_Poor	3658	900	1000	2,4	0,1730	19	Very_Poor	3371	900	1000	2,5	0,1560
17	Very_Poor	3658	1000	1100	2,0	0,1359	19	Very_Poor	3371	1000	1100	2,4	0,2090
17	Very_Poor	3658	1100	1200	2,4	0,2289	19	Very_Poor	3371	1100	1200	2,5	0,1993
17	Very_Poor	3658	1200	1300	2,3	0,2137	19	Very_Poor	3371	1200	1300	2,9	0,2517
17	Very_Poor	3658	1300	1400	2,1	0,1701	19	Very_Poor	3371	1300	1400	3,3	0,2277
17	Very_Poor	3658	1400	1500	2,3	0,1501	19	Very_Poor	3371	1400	1500	3,0	0,1899
17	Very_Poor	3658	1500	1600	2,4	0,1875	19	Very_Poor	3371	1500	1600	2,6	0,1817
17	Very_Poor	3658	1600	1700	2,5	0,1910	19	Very_Poor	3371	1600	1700	2,9	0,2077
17	Very_Poor	3658	1700	1800	2,4	0,2134	19	Very_Poor	3371	1700	1800	2,8	0,1895
17	Very_Poor	3658	1800	1900	2,7	0,1856	19	Very_Poor	3371	1800	1900	2,7	0,1904
17	Very_Poor	3658	1900	2000	2,0	0,1865	19	Very_Poor	3371	1900	2000	2,5	0,1840
17	Very_Poor	3658	2000	2100	2,8	0,1803	19	Very_Poor	3371	2000	2100	2,6	0,1729
17	Very_Poor	3658	2100	2200	2,2	0,1625	19	Very_Poor	3371	2100	2200	2,5	0,1838
17	Very_Poor	3658	2200	2300	2,4	0,2955	19	Very_Poor	3371	2200	2300	2,7	0,1736
17	Very_Poor	3658	2300	2400	2,8	0,3019	19	Very_Poor	3371	2300	2400	2,9	0,1818
17	Very_Poor	3658	2400	2500	3,0	0,2190	19	Very_Poor	3371	2400	2500	2,6	0,1638
17	Very_Poor	3658	2500	2600	2,6	0,3882	19	Very_Poor	3371	2500	2600	3,0	0,2007
17	Very_Poor	3658	2600	2700	2,6	0,2328	19	Very_Poor	3371	2600	2700	3,1	0,2111
17	Very_Poor	3658	2700	2800	1,5	0,1290	19	Very_Poor	3371	2700	2800	2,6	0,1670
17	Very_Poor	3658	2800	2900	2,4	0,1885	19	Very_Poor	3371	2800	2900	3,0	0,1622
17	Very_Poor	3658	2900	3000	2,5	0,2228	19	Very_Poor	3371	2900	3000	2,8	0,1976
17	Very_Poor	3658	3000	3100	2,8	0,2371	19	Very_Poor	3371	3000	3100	2,5	0,1696
17	Very_Poor	3658	3100	3200	1,9	0,1510	19	Very_Poor	3371	3100	3200	2,5	0,1628
17	Very_Poor	3658	3200	3300	2,6	0,1842	19	Very_Poor	3371	3200	3300	2,6	0,1845
17	Very_Poor	3658	3300	3400	3,1	0,2271	19	Very_Poor	3371	3300	3371	2,3	0,2583
17	Very_Poor	3658	3400	3500	2,5	0,1888	20	Very_Poor	2718	0	100	2,6	0,2149
17	Very_Poor	3658	3500	3600	2,9	0,2741	20	Very_Poor	2718	100	200	2,6	0,2897
17	Very_Poor	3658	3600	3658	2,7	0,2985	20	Very_Poor	2718	200	300	2,9	0,2840
18	Very_Poor	1802	0	100	3,6	0,6109	20	Very_Poor	2718	300	400	2,9	0,3022
18	Very_Poor	1802	100	200	2,1	0,1552	20	Very_Poor	2718	400	500	3,2	0,2940
18	Very_Poor	1802	200	300	2,6	0,2219	20	Very_Poor	2718	500	600	2,9	0,2604
18	Very_Poor	1802	300	400	2,4	0,1814	20	Very_Poor	2718	600	700	3,4	0,2350
18	Very_Poor	1802	400	500	2,8	0,1699	20	Very_Poor	2718	700	800	3,1	0,2905
18	Very_Poor	1802	500	600	2,7	0,2342	20	Very_Poor	2718	800	900	2,9	0,2438
18	Very_Poor	1802	600	700	3,9	0,4860	20	Very_Poor	2718	900	1000	3,2	0,2637
18	Very_Poor	1802	700	800	2,2	0,2611	20	Very_Poor	2718	1000	1100	2,4	0,1772
18	Very_Poor	1802	800	900	2,6	0,2514	20	Very_Poor	2718	1100	1200	2,5	0,1968
18	Very_Poor	1802	900	1000	3,1	0,2214	20	Very_Poor	2718	1200	1300	2,6	0,1889
18	Very_Poor	1802	1000	1100	2,6	0,1973	20	Very_Poor	2718	1300	1400	2,6	0,2166
18	Very_Poor	1802	1100	1200	2,3	0,1498	20	Very_Poor	2718	1400	1500	2,9	0,2563
18	Very_Poor	1802	1200	1300	2,4	0,2026	20	Very_Poor	2718	1500	1600	2,7	0,2258
18	Very_Poor	1802	1300	1400	2,3	0,1543	20	Very_Poor	2718	1600	1700	2,7	0,2745
18	Very_Poor	1802	1400	1500	2,7	0,2403	20	Very_Poor	2718	1700	1800	3,2	0,2843
18	Very_Poor	1802	1500	1600	2,7	0,1995	20	Very_Poor	2718	1800	1900	2,8	0,2476
18	Very_Poor	1802	1600	1700	2,2	0,1422	20	Very_Poor	2718	1900	2000	2,8	0,2546
18	Very_Poor	1802	1700	1802	2,4	0,1769	20	Very_Poor	2718	2000	2100	2,9	0,2697
							20	Very_Poor	2718	2100	2200	3,9	0,4331
							20	Very_Poor	2718	2200	2300	3,3	0,4676
							20	Very_Poor	2718	2300	2400	3,0	0,3288
							20	Very_Poor	2718	2400	2500	3,0	0,3445
							20	Very_Poor	2718	2500	2600	3,3	0,4480
							20	Very_Poor	2718	2600	2700	2,7	0,3235
							20	Very_Poor	2718	2700	2718	2,0	0,1357

APPENDIX C – REPRESENTATIVE & ANALOGOUS AIRCRAFT

- **Aircraft Class I**, Weight group “Less than 70,000 kg”
- Representative aircraft: DC-9-41
- Analogous aircraft: E-190

- Landing gear configuration

- **Aircraft Class II**, Weight group “70,000 to 140,000 kg”
- Representative aircraft: B727-100
- Analogous aircraft: B737-800 / MAX 8

- Landing gear configuration

- **Aircraft Class III**, Weight group “140,000 to 210,000 kg”
- Representative aircraft: DC-10 CF
- Analogous aircraft: B767-300 ER

- Landing gear configuration

- **Aircraft Class IV**, Weight group “greater than 210,000 kg”
- Representative aircraft: B747 SP
- Analogous aircraft: B747-400

- Landing gear configuration

➤ General characteristics

	DC-9-41	E-190 AR	B727-100	B737-800/MAX 8	DC-10 CF	B767-300 ER	B747 SP	B747-400
Maximum Takeoff Weight (MTOW)	51710	51800	72600	70534	199581	186880	285700	362874
Length, m	38,28	36,24	40,59	39,47	55,55	54,94	55,85	69,85
Wingspan, m	28,44	28,72	32,92	34,32	47,35	47,57	59,64	64,92
Height, m	8,7	10,6	10,4	12,62	17,53	16,03	20,06	19,51
Max cruising speed, km/h	880	850	965	828	865	851	990	913
Cruising altitude, m	10600	12500	12000	12500	12800	12800	13700	12500
Range, km	3100	4400	5300	5700	10000	11000	12300	14200
Usable fuel capacity, L	13926	16029	29069	26022	82376	91380	184630	204333
Max seating capacity, pass.	125	106	106-131	160-184	255-399	261-290	297 A 331	400
Seat configuration, rows	3+2	2+2	3+3	3+3	2+5+2/3+4+3	2+3+2	3+4+3	3+4+3
Max cargo volume, m ³	28,9	22,63	25	44,1	130,17	114,1	110	181
Cockpit length, m	3,1	2,7	3,5	3,5	5,8	4,7	6,1	6,1
Cockpit height, m	2	2	2,1	2,2	2,4	1,7	2,4	2,4
Min runway length for takeoff, m	1800	2000	1700	2400	2800	2400	2800	3000
Engines	2 PW	2 GE	3 PW	2 GE	3 GE	2 PW/GE	4 RR/PW	4 PW/GE
First flight, year	1967	2004	1963	1997	1972	1981	1975	1988

➤ Aircraft tires

Aircraft	Rated Speed (mph)	Main gear		Nose gear	
		Size	Ply Rating	Size	Ply Rating
DC-9-41	225	41*15 - 18	22	26*6.6	Type VII
E-190 AR	225	H 41*16 - 20	22	24*7.7	16
B727-100	225	49*17	26 Type VII	32*11.5	Type VIII
B737-800	225/235	H 44.5*16.5 - 21	28	27*7.75 - 15	12
B737 MAX 8	225/235	H 44.5*16.5 R 21	30	27*7.75 R 15	12
DC-10 CF	225	50*20 - 20	32	37*14 - 14	24
B767-300 ER	225/235	H 46*18 - 20	32	H 37*14 - 15	22
B747 SP	225	46*16	28	49*17	32
B747-400	225/235/245	H 49*19 - 22	32	49*17	32

➤ Maximum Pavement Loads (static)

Maximum Pavement Loads (static)								
Aircraft	MTOW (Kg)	MDTW (Kg)	V _{NG}		V _{MG} (per strut)	H (per strut)		Approximate weight on the main landing gear, %
			Static at most forward CG	Static plus force due to braking at most forward CG	Maximum load occurring at static after CG	At steady braking 3m/seg ² deceleration	At instantaneous braking (coefficient of friction = 0,8)	
DC-9-41	51710	52163	5167	7811	24411 (2)	8101 (2)	17265 (2)	93,2
E-190 AR	51800	51960	6347	8927	23952 (2)	7005 (2)	16593 (2)	92,2
B727-100	72600	73100	7800	11500	34900 (2)	11300 (2)	27900 (2)	95,4
B737-800	70534	70760	7607	11571	39047 (2)	10968 (2)	27442 (2)	93,6
B737 MAX 8	82191	82417	7170	11852	38461 (2)	12799 (2)	30769 (2)	93,6
DC-10 CF	199581	207746	22790	38537	96923 (2)	32433 (2)	77538 (2)	92,8
B767-300 ER	186880	187339	20108	30690	86546 (2)	29093 (2)	69237 (2)	92,4
B747 SP	285700	288500	41200	60450	66750 (4)	22400 (4)	53400 (4)	87,8
B747-400	362874	364235	42350	62700	86850 (4)	28300 (4)	69500 (4)	93,3

Note: All loads calculated using airplane Maximum Design Taxi Weight (MDTW), also known as Maximum Ramp Weight (MRW)

V_{NG} = Maximum Vertical Nose-gear ground load at most forward CG, kg

V_{MG} = Maximum Vertical Main-gear ground load at most aft CG, kg

H = Maximum Horizontal ground load from braking, kg

(1) = 1 strut
(2) = 2 struts
(4) = 4 struts

➤ Representative vs. Analogous aircraft operating at the São Paulo/Guarulhos International Airport by Airline.

- Access in 09/12/2018
- <http://www.aeroporto-guarulhos.net/companhias-aereas-aeroporto-guarulhos>

Airline/Aircraft	DC-9-41	Embraer 190/195	B727-100	737-800	737-8 MAX	DC-10	B767-300	B747-SP	B747-400
Aerolineas Argentinas				31	5				
Air Canada		25			17		6		
Air Europa				20					
American Airlines		20		304	14		24		
Austral		26							
Azul		63							
British Airways							5		36
Aeromexico		47		38	4				
Air China				115	11				6
Boliviana de Aviacion				2			4		
Copa Airlines Panama		14		68					
Etihad Airways									1
Korean Air				11					7
Lufthansa									13
Delta Airlines				77			58		
Ethiopian Airlines				14	2		6		
GOL				91	2				
KLM				27					15
LATAM							26		
Royal Air Maroc		4		31			4		1
Turkish Airlines				62	1				
Singapore Airlines									7
Avianca Central America (old TACA)		8							
Tame		2							
United Airlines				141			36		
TOTAL	0	209		1032	56	0	169	0	86

APPENDIX D – SIMULATIONS OUTPUT EXAMPLES

Profile 3 (Very Good); Aircraft Class I and IV (B-727 & B-747); 40 knots (74 km/h)

Profile 3 (Very Good); Aircraft Class I and IV (B-727 & B-747); 100 knots (185 km/h)

Profile 3 (Very Good); Aircraft Class I and IV (B-727 & B-747); 160 knots (296 km/h)

Profile 9 (Good); Aircraft Class I and IV (B-727 & B-747); 40 knots (74 km/h)

Profile 9 (Good); Aircraft Class I and IV (B-727 & B-747); 100 knots (185 km/h)

Profile 9 (Good); Aircraft Class I and IV (B-727 & B-747); 160 knots (296 km/h)

Profile 12 (Regular); Aircraft Class I and IV (B-727 & B-747); 40 knots (74 km/h)

Profile 12 (Regular); Aircraft Class I and IV (B-727 & B-747); 100 knots (185 km/h)

Profile 12 (Regular); Aircraft Class I and IV (B-727 & B-747); 160 knots (296 km/h)

Profile 16 (Poor); Aircraft Class I and IV (B-727 & B-747); 40 knots (74 km/h)

Profile 16 (Poor); Aircraft Class I and IV (B-727 & B-747); 100 knots (185 km/h)

Profile 16 (Poor); Aircraft Class I and IV (B-727 & B-747); 160 knots (296 km/h)

Profile 20 (Very Poor); Aircraft Class I and IV (B-727 & B-747); 40 knots (74 km/h)

Profile 20 (Very Poor); Aircraft Class I and IV (B-727 & B-747); 100 knots (185 km/h)

Profile 20 (Very Poor); Aircraft Class I and IV (B-727 & B-747); 160 knots (296 km/h)

APPENDIX E – AIRCRAFT DYNAMIC RESPONSES VS. IRI

Maximum vertical accelerations by aircraft class as a function of speed when IRI range is “Very Good” (<1.0 m/km).

IRI range Very Good (< 1.0 m/km)

Maximum vertical accelerations by aircraft class as a function of speed when IRI range is “Good” (1.0 – 1.5 m/km).

Maximum vertical accelerations by aircraft class as a function of speed when IRI range is “Regular” (1.5 – 2.0 m/km).

IRI range Regular (1.5 - 2.0 m/km)

Very Low (20 - 40 knots)

Low (60 - 80 knots)

Medium (100 - 120 knots)

High (140 - 160 knots)

Very High (180 - 200 knots)

Maximum vertical accelerations by aircraft class as a function of speed when IRI range is “Poor” (2.0 – 2.5 m/km).

Maximum vertical accelerations by aircraft class as a function of speed when IRI range is “Very Poor” (> 2.5 m/km).

IRI range Very Poor (> 2.5 m/km)

Maximum pavement load ratios by aircraft class as a function of speed when IRI range is “Very Good” (< 1.0 m/km).

Maximum pavement load ratios by aircraft class as a function of speed when IRI range is “Good” (1.0 – 1.5 m/km).

IRI range Good (1.0 - 1.5 m/km)

Maximum pavement load ratios by aircraft class as a function of speed when IRI range is “Regular” (1.5 – 2.0 m/km).

Maximum pavement load ratios by aircraft class as a function of speed when IRI range is “Poor” (2.0 – 2.5 m/km).

IRI range Poor (2.0 - 2.5 m/km)

Maximum pavement load ratios by aircraft class as a function of speed when IRI range is “Very Poor” (> 2.5 m/km).

APPENDIX F – STATISTICAL APPROACH

Statistical analyses in this research take into account maximum or peak (MAX) values as well as average (RMS) values. RMS, also known as quadratic mean, is a kind of refined arithmetic mean that takes into account the standard deviation of a set of numbers. Thus, if $\bar{x}$ is the arithmetic mean and σ_x is the standard deviation of a set of numbers then:

$$RMS = \sqrt{(\bar{x}^2) + (\sigma_x^2)} \quad (1)$$

In order to improve the normality of the data and, consequently, improve the regression model, data transformation was used in this research. Osborne (2010) argues that the application of a transformation technique reduces the chances of committing either a Type I or Type II statistical errors. According with Shuttleworth & Wilson (2018) these errors are associated to statistical hypothesis testing. Essentially, Type I error is the rejection of a true null hypothesis (also known as a "false positive" finding), while a type II error is failing to reject a false null hypothesis (also known as a "false negative" finding). There are several traditional data transformations for improving normality such as Square Root Transformation, Log Transformation, Inverse Transformation, Arcsine Transformation, Box-Cox Transformation, among others. The Square Root transform was adopted for this research and the statistical software IBM SPSS Statistics 22 was used to carry out the statistical comparisons and regression analyses.

The method used for the statistical comparisons described above is the Pearson Product Moment Correlation (PPMC). It is the most common measure of correlation and is more widely known as Pearson Correlation. In general, two letters are used to represent the Pearson Correlation: Greek letter rho (ρ) for a population and the letter "r" for a sample in order to reflect the degree of linear relationship between two variables. A Pearson correlation is a number between -1 and +1 that indicates the extent to which two variables are linearly related (SPSS, 2018). A Pearson correlation between variables X and Y is calculated by:

$$r_{XY} = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (2)$$

Conversely, once dependent and independent variables are continuous and has an approximately normal distribution after the using the transformation, Simple Linear Regression Analysis was used, a technique that predicts a metric variable from a linear relation with another metric variable. Any linear relation can be defined by the following equation:

$$Y' = A + B * X \quad (3)$$

Where X is the predictor (present in the data), B is the coefficient (estimated by regression), A is the intercept (estimated by regression), and Y' is the predicted value (calculated from A, B and X). The coefficient is the number of units increase in Y associated with one unit increase in X. Correspondingly; the intercept is the predicted outcome for cases that score 0 on the predictor.

On the other hand, additional concepts such as residuals, R-squared and R-squared adjusted are also involved in regression analysis. A regression residual is the observed value - the predicted value on the outcome variable for some case. R-square is the proportion of variance in the outcome variable that's accounted for by regression. R-square adjusted is an unbiased estimator of r-square in the population (SPSS, 2018). Regression residuals were presented through scatter plots and can be conferred in Appendix F. R-squared and R-squared adjusted values were also provided.

From a matricial point of view, a set of simple linear regression models also has the form:

$$Y = x\beta + \varepsilon \quad (4)$$

Where Y is the $n \times m$ response matrix; x is the $n \times (p+1)$ design matrix; β is $(p+1) \times m$ matrix coefficients; and ε is the $n \times m$ error matrix. Therefore, matrix form writes this model for all $n \times m$ points simultaneously:

$$\begin{pmatrix} y_{11} & \cdots & y_{1m} \\ y_{21} & \cdots & y_{2m} \\ y_{31} & \cdots & y_{3m} \\ \vdots & \ddots & \vdots \\ y_{n1} & \cdots & y_{nm} \end{pmatrix} = \begin{pmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1p} \\ 1 & x_{21} & x_{22} & \cdots & x_{2p} \\ 1 & x_{31} & x_{32} & \cdots & x_{3p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{np} \end{pmatrix} \begin{pmatrix} b_{01} & \cdots & b_{0m} \\ b_{11} & \cdots & b_{1m} \\ b_{21} & \cdots & b_{2m} \\ \vdots & \ddots & \vdots \\ b_{p1} & \cdots & b_{pm} \end{pmatrix} + \begin{pmatrix} e_{11} & \cdots & e_{1m} \\ e_{21} & \cdots & e_{2m} \\ e_{31} & \cdots & e_{3m} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nm} \end{pmatrix} \quad (5)$$

APPENDIX G – RESIDUALS

Scatterplots of standardized residuals shows that only vertical acceleration data meet the assumptions of homogeneity of variance and linearity and the residuals were approximately normally distributed.

ANNEX A – QUARTER-CAR MODEL

Source: Sayers & Karamihis (1996)

QUARTER-CAR FILTER

This filter is defined by differential equations that relate motions of a simulated quarter-car vehicle to road profile inputs. Figure 54 shows a quarter-car model, which includes the major dynamic effects that determine how roughness causes vibrations of the car body. This system is described by four first-order ordinary differential equations that can be written in matrix form:

$$\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} h_{ps} \quad (29)$$

where $\mathbf{x}$ is an array of *state variables* (variables that, together, completely describe the state of the simulated system), and the $\mathbf{A}$ and $\mathbf{B}$ arrays have coefficients in the equations:

$$\mathbf{x} = [z_s, \dot{z}_s, z_u, \dot{z}_u]^T$$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_2 & -c & k_2 & c \\ 0 & 0 & 1 & 0 \\ \frac{k_2}{\mu} & \frac{c}{\mu} & -\frac{k_1 + k_2}{\mu} & -\frac{c}{\mu} \end{bmatrix}$$

$$\mathbf{B} = [0, 0, 0, k_1/\mu]^T \quad (30)$$

The scalar constants and variables are defined as follows:

- c_s = suspension damping rate
- h_{ps} = smoothed profile elevation
- k_s = suspension spring rate
- k_t = tire spring rate
- m_s = sprung mass (portion of mass of car body supported by one wheel)
- m_u = unsprung mass (mass of the wheel, tire, and half of the axle/suspension)
- z_s = height (vertical coordinate) of sprung mass
- z_u = height (vertical coordinate) of unsprung mass
- c = c_s/m_s
- k_1 = k_t/m_s
- k_2 = k_s/m_s
- μ = m_u/m_s

Figure 54. Quarter car model.

Time derivatives are indicated with a dot (e.g., $\dot{z}_s$). The time covered over each profile sample is related to longitudinal distance by the simulated speed of the vehicle:

$$t = X/V \quad (31)$$

where X is longitudinal distance and V is the simulated forward speed, expressed in units of length per second, where the length units match those of X .

State-Space Solution

For a set of linear equations such as eq. 29, the total response at point i is the sum of the *free response* (no input) of the system to its state at a previous point $i-1$, plus the *forced response* to an input over the interval between points $i-1$ and i . In the case that the input is a constant, the response can be written

$$\mathbf{x}_i = \mathbf{S} \mathbf{x}_{i-1} + \mathbf{P} \mathbf{u} \quad (32)$$

where $\mathbf{S}$ is a 4×4 *state transition* matrix that defines the free response as a linear combination of the four variables in $\mathbf{x}$ at point $i-1$, and $\mathbf{P}$ is a 4-element *partial response* array that defines the forced response as a linear function of a constant $\mathbf{u}$ that is the input over the interval from $i-1$ to i . $\mathbf{S}$ and $\mathbf{P}$ are solutions of the equations, calculated from the matrices in eq. 29:

$$\mathbf{S} = e^{\mathbf{A} \Delta/V} \quad (33)$$

$$\mathbf{P} = \mathbf{A}^{-1} (\mathbf{S} - \mathbf{I}) \mathbf{B} \quad (34)$$

where e is the base of the natural logarithms, Δ is the interval between profile samples, and $\mathbf{I}$ is a 4×4 identity matrix. Eq. 33 requires taking e to a matrix power. One method is to use a Taylor series expansion:

$$e^{A \Delta/V} = I + \sum_{i=1}^N \frac{A^i (\Delta/V)^i}{i!} \quad (35)$$

where N is a number large enough to obtain the required accuracy.

Research of different interpolation methods showed that the best approximation is the assumption that the profile slope is constant between samples.⁽⁵⁾ This means that to obtain the best accuracy, the assumed constant input u in eq. 32 should be profile slope.

Replacing profile height with profile slope in eq. 32 changes the physical meaning of the state variables. As written in eq. 30, with no scale factors, the units of z_s and z_u are the same as those of the input, h_{ps} . Because the describing equations (eq. 30) are linear, they can be applied to other types of inputs, such as smoothed profile slope:

$$\dot{\mathbf{x}} = \mathbf{A} \mathbf{x} + \mathbf{B} s_{ps} \quad (36)$$

where s_{ps} is smoothed profile slope, and the array $\mathbf{x}$ is redefined in terms of filtered slope variables s_s and s_u

$$\mathbf{x} = [s_s, \dot{s}_s, s_u, \dot{s}_u]^T \quad (37)$$

Profile slope over an interval B (see figure 54) is computed with the difference equation:

$$s_{ps,i} = \frac{h_{p,i+k} - h_{p,i}}{k\Delta} \quad (38)$$

where

$$k = \max[1, \text{nint}(B/\Delta)] \quad (39)$$

The function *max* means "take the maximum of the two arguments," and the function *nint* means "round off to the nearest integer." B is the moving average base length. For example, if the sample interval is $\Delta=6$ in (152 mm) and the base length is 9.8 in (250 mm), the ratio (B/Δ) is 1.64, which is rounded to 2. The number 2 is larger than 1, so the value of k would be 2.

To solve differential equations such as eq. 29, one must know or estimate the values of the state variables at some starting time. The response obtained over a profile includes a response of the transition from the assumed initial values to the profile-induced response. The effect of the initialization diminishes as the simulated car covers more of the profile. The best way to deal with the initialization is to measure the profile for some distance ahead of the site and start the simulation there. However, a requirement that extra profile be measured and stored is not always practical. Therefore, z_s and z_u are initially set to match the height of the first profile point, and $\dot{z}_s$ and $\dot{z}_u$ are set to match the average change in profile height per second over some length of profile at the start.

To initialize the algorithm, the elements of the $\mathbf{x}$ array for $i=1$ are set as:

$$\mathbf{x}_1 = [(h_{p,L_0/\Delta} - h_{p,1})/L_0, 0, (h_{p,L_0/\Delta} - h_{p,1})/L_0, 0] \quad (40)$$

where L_0 is the initialization length.

Accumulator

In order for the quarter-car filter to yield a summary index, some combination of the calculated responses (the z 's) must be accumulated over the length of the simulation as follows:

$$PI = \left(\frac{1}{L} \int_0^{L/V} |r|^p dt \right)^{\frac{1}{p}} \quad (41)$$

where PI is a summary profile index, r is some combination of the vehicle response variables, L is the length of the profile, V is velocity, t is time, and p is some exponent. The vehicle response variables oscillate about zero, and have zero as their average values. The absolute value in eq. 41 is needed in case the exponent, p , is less than 1.

INTERNATIONAL ROUGHNESS INDEX

The IRI is calculated using the quarter-car model described in the previous section. The vehicle properties used for the IRI are known as the *Golden Car* parameters:

$$\begin{aligned} c &= 6. \quad (1/s) \\ k_1 &= 653. \quad (1/s^2) \\ k_2 &= 63.3 \quad (1/s^2) \\ \mu &= 0.15 \quad (-) \\ V &= 80 \quad (km/h) \end{aligned}$$

Other parameters specific to the IRI are:

$$\begin{aligned} L_0 &= 11. \quad (m) \\ B &= 250. \quad (mm) \end{aligned}$$

The IRI is accumulated using:

$$r = \dot{z}_s - \dot{z}_u \quad (42)$$

and $p = 1$. Thus, the IRI represents average rectified slope. Over a number of profile samples (n):

$$IRI = \frac{1}{n} \sum_{i=1}^n |s_{s,i} - s_{u,i}| \quad (43)$$

ANNEX B – DAMPING FACTORS

Fundamental mode viscous damping ratio for metal and composite stiffened panel type structures.

Soovere & Drake (1985) developed a basic design guide for the application of viscoelastic damping to primarily aerospace structures. The guide addresses topics about the factors contributing to vibration problems in aerospace type structures and presents a summary of material properties for typical aerospace metals and composite materials. The default value 0.025 used in ProFAA is suitable for most of the type structures listed in the Figure.

Structures	Average Viscous Damping Ratio ζ	Typical Range of Measured Data	
		Minimum ζ	Maximum ζ
Riveted aluminum skin-stringer panels both flat and curved with and without sealant	0.0145	0.005	0.05
Riveted titanium skin-stringer panels	0.0145	0.008	0.03
Riveted aluminum box structure	0.0145	0.008	0.04
Bonded aluminum skin-stringer panels	0.0125	0.009	0.022
Bonded and integrally stiffened graphite/epoxy panels	0.0125	0.0042	0.047
Bonded and integrally stiffened Kevlar cloth panels	0.020*	0.012*	-
Graphite/epoxy box structure assembled with fasteners	0.004	Only one tested	
Fastener attached stiffened metal and graphite/epoxy honeycomb panels	0.019	0.013	0.027
Fastener attached stiffened Kevlar honeycomb panels	0.027	Only two tested	
Corrugated and closely spaced hat stiffened aluminum panel structure	0.017	0.014	0.019
Built-up aluminum structures with integrally machined skins	0.0057	0.0019	0.0145
Riveted chemically milled aluminum panels (expected to be the same as skin-stringer panels but at higher frequency).	0.0145*	-	-

*Estimated.

ANNEX C – PILOT'S QUESTIONNAIRE SAMPLE

Source: Horn (1977)

INFORMATION TO BE OBTAINED FROM OPERATIONS OFFICERS

FOLLOWING QUESTIONS TO BE ANSWERED BY B-52 AND KC-135 PILOTS.

1. WHAT TYPE AIRCRAFT DO YOU FLY?
2. HOW LONG HAVE YOU BEEN STATIONED AT THIS BASE?
3. WHERE WERE YOU STATIONED PRIOR TO THIS ASSIGNMENT?
4. HAVE YOU EVER FELT UNCOMFORTABLE FROM THE STANDPOINT OF RIDEABILITY WHILE TAKING OFF OR LANDING A B-52 OR KC-135 ON THE RUNWAY AT THIS AIR BASE?
5. HAVE THERE EVER BEEN TIMES IN A B-52 ON THIS AIRFIELD DURING TAKEOFF OR LANDING THAT IT WAS DIFFICULT TO READ THE INSTRUMENTS BECAUSE OF VIBRATIONS OR SHAKING OF DIALS CAUSED BY ROUGHNESS OF PAVEMENT?
6. HAVE YOU EVER EXPERIENCED THE FEELING WHILE MOVING DOWN THE RUNWAY AT THIS AIRFIELD THAT, DUE TO OSCILLATIONS OF THE AIRCRAFT CAUSED BY UNEVENNESS OF THE PAVEMENT, YOU WERE AIRBORNE WHEN YOU REALLY WERE NOT?
7. FROM YOUR EXPERIENCE IN LANDINGS AND TAKEOFFS AT THIS AIR BASE, HAVE YOU FOUND THE RUNWAY LESS SMOOTH IN WINTER/SPRING THAN IN SUMMER/FALL?
8. HOW WOULD YOU RATE THE SMOOTHNESS CHARACTERISTICS OF THE RUNWAY AT THIS AIR BASE? SMOOTH ☐ ; FAIR ☐ ; ROUGH ☐
9. HOW MANY SAC AIRFIELDS HAVE YOU HAD THE OPPORTUNITY TO OPERATE FROM IN THE CONTINENTAL UNITED STATES?
10. FROM YOUR EXPERIENCE, DO YOU KNOW OF ANY SAC AIRFIELDS THAT YOU WOULD CONSIDER AS VERY ROUGH FROM THE STANDPOINT OF RIDING QUALITY?

Figure 3. Example of questionnaire distributed to B-52 and KC-135 pilots