DEVELOPMENT OF RELATIONSHIPS BETWEEN PCI, RESILIENT MODULUS AND IRI USING LTPP DATABASE AND THEIR VALIDATION ON M2

By

MUHAMMAD USAMA UMAR

(Registration No: 00000274307*)*

Department of Transportation Engineering

School of Civil and Environmental Engineering (SCEE),

National University of Sciences and Technology (NUST),

Sector H-12 Islamabad, Pakistan

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Thesis supervisor: Dr. Arshad Hussain

Department of Transportation Engineering

School of Civil and Environmental Engineering (SCEE),

National University of Sciences and Technology (NUST),

Sector H-12 Islamabad, Pakistan

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DEDICATION

This thesis is dedicated to my beloved parents and teachers whose guidance and prayers enabled me to get higher education without any hindrances. They tried their utmost to avoid me from any disconnection from my studies. They are highly rated people and would always be respected. I pray for their long and healthy lives.

May they live long.

(Ameen).

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ABSTRACT

The pavement performance is the ability of the pavement to serve the traffic over a period of time. And Pavement performance evaluation is determination of performance using parameters like International Roughness Index (IRI), Pavement Condition Index (PCI), and rutting etc. Many researchers have been developing relationships between pavement distresses and indices. They have used regression analysis, Multivariate Adaptive Regression Splines (MARS), and Artificial Neural Network (ANN). Among the variables used by the researchers, IRI is most commonly used and termed as best characteristic reflecting the pavement distresses and corresponding performance.

This research aims to examine and develop relationships between PCI, IRI and FWD back calculated Resilient Modulus (Mr) under temperature and climatic constraints using long term pavement performance (LTPP) database. The relationships developed will be validated on Pakistani motorway M2. The various tests, IRI, and FWD are performed by NHA on Motorway M2 in 2014 and their data are retrieved from the design report of 2014 for this research. Data of 193 sections belonging to wet, no freeze and dry, no freeze regions are obtained from LTPP database. These sections are located at the regions where average annual temperature ranges from 20^{o} C to 30^{o} C.

Relationships between IRI, PCI, and back calculated resilient modulus (Mr) of three typical layers of the pavement are examined and developed. Multiple Linear Regression technique is used to develop the relationships. The relationships are assessed with the help of p-value and R2 values. P-value of all three equations is less than 0.05 which makes the equations "significant". PCI is found to be dependent variable whereas IRI and Mr are independent variables while examining and developing relationships among these three variables. Furthermore, model validation between estimated PCI and actual PCI for three layers; asphalt layer, base course layer and sub grade layer of motorway M2 presented a better R2 of 0.68, 0.61 and 0.68 respectively indicating a good model. It is concluded that a relationship between the back calculated Mr, IRI, and PCI exists. This research may also help decision makers to predict the resilient modulus and/or determine PCI for the highways and motorways on network level and carryout necessary decisions regarding prioritizing highways/motorways for funding, pavement service life, surface treatments, and pavement rehabilitation etc.

Keywords: LTPP, PCI, IRI, FWD testing, Pavement Performance

Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

1.1 Background

The pavement performance is the ability of the pavement to serve the traffic over a period of time. And Pavement performance evaluation is determination of performance using parameters like PCI, IRI, and rutting etc. Many researchers have been developing relationships between pavement distresses and indices. They have used regression analysis, ANN and MARS. Among the variables used by the researchers, IRI is most commonly used and termed as best characteristic reflecting the pavement distresses and corresponding performance. This research aims to develop and evaluate relationships between IRI, PCI, and Resilient Modulus (E or M_r) under temperature and climatic constraints using LTPP database. The relationships developed will be validated on Pakistani motorways. Data of 193 sections belonging to wet, no freeze and dry, no freeze regions are obtained. These sections are located at the regions where average annual temperature ranges from 20^o C to 30^o C. These filters are adopted to get the LTPP sections which experienced same climatic and temperature conditions as that of Pakistan.

Jia evaluated long term effectiveness of the maintenance treatments using LTPP data (Jia et al., 2020). Radwan et al., have developed distress prediction models using LTPP database. They used six distresses to carry out prediction model generation (transverse cracking, longitudinal cracking, fatigue cracking, bleeding, raveling, and rut depth) (Radwan et al., 2020). Moreover, simplified PCI regression model is also found developed in relation with IRI. Authors used 1448 LTPP sections from General Pavement Studies (GPS) and Special Pavement Studies (SPS). They found that sigmoid function best represents the relationship between IRI and PCI. They achieved coefficient of determination (R^2) 0.995. Hence, a highly strong relationship exists between PCI and IRI (Elhadidy et al., 2019b). Same struggle has also been made by few other researchers. Piryonesi & El-Diraby, 2021 developed using almost 3954 data points extracted from LTPP database. At first, the aggregate data set was used but R^2 achieved was no higher than 0.31. They then clustered the data on the basis of location and functional class with the hope to improve R^2. With this step, they obtained R^2 equal to 0.70 (Piryonesi et al., 2021). They also used Ontario Ministry of Transportation (MTO) data to develop stronger correlations and later on suggested using MTO data over LTPP data.

Many researchers have also tried to correlate roughness with the structural performance of the pavement. To name a few (Fakhri & Shahni Dezfoulian, 2019a; Sollazzo et al., 2017). Sollazzo, Fwa, & Bosurgi, 2017 tried to develop relationship between roughness and effective Structural number using Artificial Neural Network (ANN) but interestingly, Fakhri & Shahni Dezfoulian, 2019 used data from 318 sections in Iran to develop relationships between IRI, Pavement Surface Evaluation and Rating index (PASER) and deflection bowl parameters derived from Falling Weight Deflect meter (FWD). They developed structural indices of each pavement layer and developed the relationships using regression and ANN. They developed indices of base layer, middle layer and lower layer denoted as BLI, MLI and LLI and correlated each of them with the IRI and PASER. They successfully determined the relationships between these three parameters.

This research aims to develop and examine relationships between IRI, PCI and resilient modulus back calculated from FWD test. The developed relationships will then be validated with the data obtained from field data of Pakistani Motorways M2.

1.2 Problem Statement

Many researchers have keenly worked on deriving relationships between roughness and distress types. Many worked to evaluate the pavements structurally using IRI, PCI, PCR, PASER, Structural Number, and pavement layer indices etc. From the practice of researchers mentioned above, it is deduced that the wide research opportunities are present regarding developing relationships between pavement condition indices and structural evaluation. This research aims to examine or cast light on the relationships between IRI, PCI and E (derived from FWD back calculation). Later on, the relationships developed will be validated with the data obtained from M2. This research will try to pave the way for future researchers to develop the relationships using LTPP database and validate on Pakistani Motorways. This initiative will help to reduce pavement monitoring and testing costs and enhance decision making regarding service life of the pavements.

1.3 The Objective of the Study

The Objectives of this research are stated below:

- Examine and develop the relationships between IRI, PCI, and Resilient Modulus (back calculated from FWD) using LTPP database.
- Validate the relationships using data obtained from NHA for Pakistan Motorway M2.

1.4 Justifications

The justification of this research is as follows;

- The research (Fakhri & Shahni Dezfoulian, 2019b) was highly useful and also inspiring. Their developed models give a satisfactory correlation between IRI, Pavement Surface Evaluation and Rating index (PASER) and structural indices (ROC, BLI, MLI, and LLI) which are based on deflection measurements. While the Base Layer Index (BLI) and Middle Layer Index (MLI) both reveal the condition of the base layer and subbase layer, respectively, the radius of curvature (ROC) is more representative of the surface (asphalt) and base layer. Additionally, the Lower Layer Index (LLI) depicts the subgrade's structural reaction. After inspiring from this research, the relationship between IRI, PCI and back calculated resilient modulus has been developed.

- Due to the repetition of traffic load on the road, road becomes more stiff and result resilient modulus also increases. Due to stiffness of road, rate of deterioration increases as elasticity of pavement decreases. In result, various cracks occur on the surface of road and need maintenance and rehabilitation before the completion of design life. As the relationship between IRI, PCI and Mr has been developed in this research. So this research may help decision makers to predict the resilient modulus using the developed equation and carry out necessary treatments to enhance the design life of pavement.

1.5 Thesis Organization

This report is partitioned into the following five chapters; short description of each chapter is given below:

1.5.1 Introduction

This chapter focuses on the brief overview of the study describing the relationships between IRI, PCI, and Resilient Modulus. This chapter also includes problem statement explaining the purpose of this research and objectives.

1.5.2 Literature Review

This chapter deliberates literature review related to the study of relationship between IRI, PCI, and Resilient Modulus and studying the various factors affecting the Resilient Modulus. Various studies of different researchers are also described and their results are compared in this chapter.

1.5.3 Methodology

This chapter elaborates the data used for this research and standard laboratory/field test methods which are used to determine the IRI, PCI and MR and an overall procedure which is followed to achieve the objectives of this research.

1.5.4 Analysis, Results and Discussions

This chapter comprises of results obtained from regression analysis. This also elaborates results and discussions on relationships between IRI, PCI, and Resilient Modulus, and their validations with the data obtained from M2.

1.5.5 Conclusions and Recommendations

This chapter summarizes the conclusions obtained from the analysis and results. Some recommendations regarding relationships are discussed and future research is suggested in this chapter.

1.6 Summary

This chapter provides an overview of the research study. It introduces the pavement management system, defines problems faced by SHAs, and gives overview of relationships among pavement condition and structural assessment parameters. It also elaborates the body of thesis and subsequent information pertaining to the chapters of the thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

State highway authorities (SHAs) now face a significant challenge regarding the preservation, maintenance, reconstruction, and rehabilitation of transportation infrastructure in general and pavement structures in particular during the last ten years. The issue is made worse by the absence of enough funding to repair the condition of the pavement network. Numerous SHAs have devised substitute procedures to address this issue and maintain their transportation networks. A number of obstacles, such as adequate finance, personnel, and the loss of knowledge, limit such approaches (Wotring et al., 1998)

Any planned maintenance tasks intended to increase the lifespan of the pavement are referred to as preventive maintenance. Reconstruction is described in the 1981 Highway Act as "the construction of the equivalent of a new pavement structure which usually involves[s] the complete removal and replacement of the existing pavement structure with new and/or recycled materials." Rehabilitation is defined as "resurfacing, restoration, and rehabilitation work undertaken to restore serviceability and to extend the service life of an existing facility" (Wotring et al., 1998)

Another fundamental part of any Pavement Management System (PMS) is the assessment of pavement performance utilizing indicators of pavement condition. Numerous metrics, including *"the Present Serviceability Rating (PSR), PCI, IRI, Pavement Condition Rating (PCR), and others"*, have been often utilized to determine maintenance plans for the pavements that are already in place (UShah et al., 2013).

In the US and Canada, the PCI technique is the most used indicator for evaluating pavement quality. PCI is an extensive assessment of the current pavement state. It also displays the structural soundness of the pavement and the state of the surface (Shahin & Kohn, 1979)

Visual inspection or image-based survey techniques are used to gather data for the PCI determination. The lengthy visual examination disrupts traffic because it takes so long. Additionally, it is impracticable for long routes and extensive networks of roads, and it might be dangerous for the inspectors themselves. Whereas, image-based survey techniques, which use a vehicle to capture photographic, video, or digital pictures of the pavement system, are quicker and safer but may also be more expensive (Elhadidy et al., 2019a)

The pavement roughness is one of the key factors influencing the ride quality and, therefore, the user's perception of the road. The rise in pavement roughness affects vehicle economy, raises fuel consumption, emits more greenhouse gases, and may compromise traffic safety, costing millions of dollars annually. The IRI may be used to measure pavement roughness (IRI). In the 1980s, the World Bank created IRI. *"According to a mathematical simulation of a quarter-car crossing a measured profile at 80 km/h",* IRI is "the cumulative suspension vertical motion divided by the distance travelled" (Guide, 2004).

The *"1993 AASHTO Guide for the Design of Pavement Structures"* uses the current serviceability index (PSI), a qualitative assessment of pavement condition, to factor in a pavement's functioning into its design equations (Officials, 1993). The deformation of the pavement surface that causes an uncomfortable or unpleasant ride is referred to as roughness. (Haas et al., 1994). Roughness has other effects, including longer travel times and greater expenses for road users (Officials, 1993).

Table 2-1 Classification of pavement conditions based on IRI (Elhadidy et al., 2019a)

Pavement Quality	**Acceptable IRI (m/km)**					
	Sayers at. (1986)	**FHWA (2003)**		**Cantisani and Loprencipe (2010)**	**INVIAS Specifications (2007)**	**Goenaga et al. (2017)**
		Interstates	**Other**			
Very poor	< 2	< 1	< 1	< 1.42	2 - 3.5	< 2.8
Good	2-3.5	1-1.5	1-1.5	1.42 - 2.84	3.5 - 4.5	2.8 - 3.5
Fair	3.5-6	1.5-1.9	1.5-2.68	2.84 - 4.06	4.5 - 6.5	3.5 - 4.3
Poor	>8	> 2.7	> 3.47	> 4.06	> 6.5	> 4.3

It is commonly known that a pavement's initial IRI has a significant impact on its IRI. (Perera et al., 1998) *"The American Association of State Highway Officials (AASHO)"* funded the Road Test, and the United Kingdom conducted a research on Kenyan road costs. The study of Lytton et al. and the *"Transport and Road Research Laboratory"* modelled the evolution of roughness as a function of traffic loads (Mactutis et al., 2000). Roughness progression as a function of time was predicted in studies by the Arizona Department of Transportation, Potter, Cheetham and Christison, and Lucas and Viano. Jordan et al pavement's model includes roughness progression as a function of time and area of cracking, while Queiroz's research linked roughness progression to both time and traffic (Mactutis et al., 2000).

2.2 Pavement deterioration

"There exist two types of pavement failures: structural failure and functional failure." The first kind, structural failure, refers to pavement constructions that are unable to support the imposed

traffic loads. The second category, referred to as functional failure, refers to pavement constructions that are unable to perform at the planned serviceability, putting passengers through pain or placing significant stress on cars due to their extreme roughness. Less roughness is accepted on high-speed expressways in particular than on minor roads with less traffic (Park et al., 2007).

Surface distresses and structural inadequacies, which are mostly brought on by constant traffic and climatic loadings, are characteristics of pavement degradation. Critical components of a pavement management system include evaluating the pavements' current state and projecting how well they will operate in the future. In this sense, scheduling and planning for maintenance are only two agency actions where pavement performance models are essential (Yamany et al., 2020). The greatest statistically significant factor in determining pavement performance has been identified as pavement age *"(Abaza 2004; Kim and Kim 2006; Rajagopal 2006)"*

2.3 Pavement performance modeling

Deterministic and stochastic pavement performance modeling are two different subfields. Model development principles, the modeling method or formulation, and model output formats are the main distinctions between deterministic and stochastic performance models "*(Amin, 2015; Li, Xie, & Haas, 1996)"*. Primary response, structural performance, function performance, and damage models for pavements are deterministic models *"(Amin, 2015; George et al., 1989)"* Mechanistic, mechanistic-empirical, and regression models are three different types of deterministic models *"(AASHTO, 1986; George et al., 1989; de Melo e Siva, Van Dam, Bulleit, & Ylitalo, 2000; Saleh, Mamlouk, & Owusu-Antwi, 2000)"*. Relationships between response characteristics like stress, strain, and deflection are drawn using mechanistic models "(Li et al., 1996)”. The link between roughness, cracking, and traffic loads is drawn via mechanistic-empirical models. A link between performance (such as the riding comfort index) and predicative factors (such as pavement thickness, pavement material qualities, traffic loads, and age) may be drawn using regression analysis (Li et al., 1996). There are several deterministic, generalized models that are created for regional or local PMSs that deal with traffic, time, and interactive-time (Attoh-Okine, 1999) (Amin & Amador-Jiménez, 2016).

2.4 Techniques for evaluation of pavement structural condition

Data on the functional and structural state of the pavement is often used to inform decisions about the choice and use of suitable pavement restoration techniques. Agencies often conduct visual distress assessments and Falling Weight Deflect metre (FWD) testing as a part of their pavement maintenance initiatives. Although calculating individual layer moduli backwards from FWD data is a standard method of evaluating a pavement's structural health, the accuracy of this method is heavily reliant on precise estimations of individual layer thicknesses. The operational restrictions of an agency may not always allow for coring operations to measure pavement layer thicknesses since they demand considerable time and resource commitments (Rabbi & Mishra, 2019).

On the other side, deflection testing is often used to check the structural integrity of pavements, frequently utilizing Falling Weight Deflect Meters (FWDs) or, more recently, Rolling Weight Deflect Meters (RWD) or Traffic Speed Deflect Meters (TSD). A pavement network that functions properly will be in excellent structural and functional condition (Rabbi & Mishra, 2019).

It would be preferable to use other (and reasonably rapid) analytical techniques to evaluate the structural health of the pavement using FWD data. Deflection Basin Parameters (DBPs), which serve as indications of the pavement deflection basin form, are one such technique. The usefulness of deflection basin parameters in assessing the structural health of in-service pavements has been highlighted by a number of researchers in the past *"(Horak 1987, Kim et al. 2000, Gopalakrishnan and Thompson 2005, Horak 2008, Donovan 2009, Talvik and Aavik 2009, Carvalho et al. 2012, Horak et al. 2015)."*

"The National Cooperative Highway Research Program (NCHRP; Kim et al. 2000)" funded one of the most major researches that included a thorough review of the pavement deflection data. For the majority of their pavement management programs, transportation agencies still depend on FWD testing at the network level to build pavement condition databases. This information, together with the outcomes of automated distress surveys, may be utilized to pinpoint structural flaws in specific pavement layers, which will eventually help in the selection and application of the best upkeep and restoration techniques. However, given the current state of practice among transportation authorities, it is still unclear how relevant FWD test data without specific information on particular pavement layer thicknesses will be (Rabbi & Mishra, 2019).

2.5 Effect of fatigue cracking on IRI

It should be mentioned that the area-based calculation is mostly used in the researches to determine the percentage of fatigue cracking. The area of longitudinal cracking in the wheel path was calculated by *"dividing the crack's length by 0.15 meters*". The sum of the longitudinal cracking and alligator cracking areas then determined the overall amount of fatigue cracking. Then, rather of using the overall area of the pavement section, the total area of fatigue cracking was split by the area of the wheel tracks. Wheel path widths were measured in the field, and it was shown that they were frequently between 0.7 and 0.8 m. (Mactutis et al., 2000)

The size of the coefficients shows how much the connection depends on the original IRI. The fatigue cracking coefficient suggests a high degree of sensitivity. *"A pavement with 100% fatigue cracks would result in an IRI increase of 0.940 m/km. The coefficient of rut depth is less sensitive. Only a modest rut depth of 25 mm (1 in) would result in a 0.212 m/km rise in IRI."* The construction of this connection did not take traffic into account since fatigue cracking and rutting were thought to be traffic-dependent characteristics (Mactutis et al., 2000)

2.6 Relationship between PCI and IRI

For instance, a surface distress index may include many forms of distresses (*"e.g., cracking, rutting, bleeding for asphalt pavement; and cracking, faulting, spalling for concrete pavement"*). The index's chosen distress categories are determined by the requirements of the agencies. As an alternative, each sort of distress might be described as a separate index. (Ctre et al., 2014)

2.6.1 Prediction of PCI using IRI

According to the research, pavement surface distresses (PCI) may affect a pavement's smoothness (IRI). The degree of surface flaws that impact how well road users ride may be represented as the smoothness or roughness of a pavement. According to research, smooth roads often result in lower operating expenses, delay costs, fuel consumption, and maintenance costs for transportation agencies throughout the course of the pavement's life. Pavement roughness is gauged using the IRI, a globally recognized criterion, via a variety of automated multipurpose measuring apparatus or devices. *"In its 2006 Strategic Plan for the National Highway System"*, the FHWA suggests a threshold for acceptable ride quality of 170 in/mi (2.7 m/km), where the smoother the ride, the lower the IRI score, and vice versa. 2015's (Arhin et al., 2015)

Table 2-2 Regression analysis using functional categorization **(Arhin et al., 2015)**

Functional Classification	**Model Equation**	**R2**
Freeways	$PCI_{FWY} = -0.215(IRI_{FWY})+110.73$	0.56
Arterials	$PCI_{ART} = -0.206(IRI_{ART})+114.15$	0.71
Collectors	$PCI_{COL} = -0.217(IRI_{COL})+115.32$	0.73
Locals	$PCI_{LOC} = -0.186(IRI_{LOC})+110.31$	0.74

2.6.2 Analysis of profile and distress data for condition evaluation

Highway authorities gather a range of data each year for the study of Pavement Management Systems (PMS) and for the purpose of monitoring pavement condition and performance prediction. Because more intricate and costly distress assessments, such as the PCI, are required, the IRI is becoming the indication of choice for pavement monitoring at the network level. The goal of this research was to determine if certain pavement surface distresses may affect the highway profile and roughness indices (e.g IRI, PSD). Over the years, researchers have looked at how road roughness is affected by pavement distresses. On whether: nonetheless, previous studies came to inconsistent findings; (Cafiso et al., 2019)

I. *"IRI and PCI are correlated"*

II. *"Such models are meaningful and transferable to scenarios reflecting different conditions than those where the databases were based on"*

Positive findings, although with low statistical significance, were obtained from a number of studies that looked at the connection between IRI and PCI. For instance, a research by Dewan et al. utilizing information from California's roads and freeways showed a linear link between the PCI and IRI. *"The suggested model demonstrated a relationship between PCI and IRI in this instance, with a coefficient of determination R2 = 53%."* With data gathered from several nations in the North Atlantic area, Park et al. demonstrated an exponential association between PCI and IRI. According to the study's findings, when other factors are taken into consideration during the model fitting procedure, PCI accounts for around 59 percent of the IRI. Arhin et al. used information from the District of Columbia from 2009 to 2012 to investigate the fluctuation of IRI and PCI. *"According to the study's findings, there is a correlation between IRI and PCI, with an R2 that varies depending on the model form from 53% to 59%."* (linear or power form). Based on information gathered for building activity zones, Vidya et al. constructed a neural network model to estimate IRI from PCI. The results shown that, even with a sample made up of sections in bad condition, the neural network could successfully predict IRI from PCI data with R2 equal to 0.86. Recent investigations, however, came to a different result. For instance, Mubaraki finds a statistically significant correlation between IRI and both cracking and rutting, but these correlations are insufficient for IRI to be utilized as a substitute for a measure of pavement quality. Arhin et al. used data from Washington DC collected over a number of years to investigate the association between IRI and PCI for various pavement and road types. According to the research, there is little relationship between IRI and PCI.

2.6.3 Evaluation of existing PCI equations

Pavement condition frequently depends on the types of distress that are visible, how severe they are, and how much of them are present. If necessary, the main challenge is figuring out how to combine these distresses into a single distress index (Bektas et al., 2014).

Establishing a new way to evaluate and rank the state of Iowa's pavements was the aim of this project. The main goal was to create new performance indicators (or PCIs) for Iowa pavements while keeping the state's present data gathering procedures intact.

The principal National Highway System (NHS), non-NHS, and all interstates in Iowa were all included in the study's data set. Pavement section data from 1998 to 2012 were included in a data collection with 11,795 data points. (The final report includes further information regarding the data and the data screening for this research) (Bektas et al., 2014)

"For PCC pavements, the Cracking Index is made up of 60% transverse cracking and 40% longitudinal cracking, while for AC surfaces, it is comprised of 20% transverse cracking, 10% longitudinal cracking, 30% wheel-path cracking, and 40% alligator cracking." The IRI, rut depth, and fault height are used, respectively, in the Riding, Rutting, and Faulting indexes. To represent the entire score, the suggested PCI-2, incorporates many metrics (Bektas et al., 2014).

For PCC and AC surface, the total PCI-2, is derived as follows (Bektas et al., 2014);

$$\text{“}PCI\text{-}2_{PCC} = 0.40\ X\ (Cracking\ index) + 0.40\ X\ (Riding\ Index) + 0.20\ X\ (Faulting\ Index)\text{”}$$

$$\text{“}PCI\text{-}2_{AC} = 0.40\ X\ (Cracking\ index) + 0.40\ X\ (Riding\ Index) + 0.20\ X\ (Rutting\ Index)\text{”}$$

2.6.4 Relation of PCI with pavement distress ratio

The distance between raw data collection points was 10 meters, and the raw data acquisition time interval was 12 months. For each yearly recorded index in each pavement segment, a 95 percent confidence interval was calculated using the Pauta criteria in order to spot and exclude aberrant data. 5,376,840 effective performance data sets were acquired by filtering and sorting. Using effective performance data in accordance with the Highway Performance Assessment Standards, the PCI, riding quality index (RQI), rutting depth index (RDI), and skid resistance index (SRI) of each distance interval and time interval were calculated (Yu et al., 2017).

PCI is the surface performance condition (Yu et al., 2017)

$$PCI = 100 - 15DR^{0.412}$$

The area of all pavement distress that has been computed in relation to the area of the measured pavement is known as the "pavement distress ratio," or "DR." There are 21 different types of distresses in asphalt pavement, including ruts, potholes, block cracking, longitudinal cracking, and transverse cracking (Yu et al., 2017).

"RQI is a measure of the pavement riding quality."

$$RQI = \frac{100}{1 + 0.026e^{0.65IRI}}$$

"The IRI for asphalt pavement is typically determined using a laser profiler.

RDI is a sign of asphalt's ongoing deformation (Yu et al., 2017).

$$RDI = 100 - 2.0RD(RD \leq 20mm)$$

$$RDI = 60 - 4.0(RD - 20)(20 \leq RD \leq 35mm)$$

$$RDI = 0(RD \geq 35mm)$$

2.6.5 Lowa pavement deterioration case study

In order to make objective judgments and carry out actions regarding pavements to be in suitable conditions at a low cost, public agencies employ PMSs (Hosseini et al., 2020).

"Departments of Transportation (DOTs)" have been adopting and setting up PMSs to suit their requirements since the early 1970s, resulting in considerable savings and an improvement in network conditions. For instance, *"the Arizona DOT saved $14 million in the first year and $101 million throughout the first four years of PMS implementation."* Using PMS, the *"Colorado Department of Transportation (CDOT)"* may spend its $740 million yearly budget for conserving and maintaining more over 9100 center-line miles in an effective manner. If PMS improvements can be developed and implemented, it appears that all of these expenses could be more cost-effective (Hosseini et al., 2020).

Conditions of pavement sections are also forecasted using various techniques, The *"Iowa Department of Transportation (Iowa DOT)"* now uses distinct deterministic regression models for each pavement segment to anticipate the future conditions of each pavement section. Deterministic models presuppose that the process being represented is not random and that observable discrepancies between expected and measured values are caused by random noise in the observation process (Hosseini et al., 2020).

As a result, a deterministic model will always generate the same result from a specific starting circumstance or initial state. The majority of deterministic models, which may be divided into empirical, mechanistic, and mechanistic-empirical models, are based on explicit regression expressions.

Using the same scale for each measure, the total PCI may be calculated using these indices, leading to the creation of a universal index for contrasting various pavement kinds. The following indicators were determined in this research using definitions from a prior study conducted for the Iowa DOT(Hosseini et al., 2020):

- *"Riding index;"*
- *"Rutting index (AC and COM Only)"*
- *"Cracking index"*
- *"Faulting index (PCC Only)"*.

Based on the coefficient values provided by lowa DOT specialists, the cracking index value for each of the three pavement types was as follows:

"Cracking index (AC and COM) = 0.2 X (Transverse sub index) + 0.1 X (Longitudinal sub index) + 0.3 X (Wheel – path sub index) + 0.4 X (Alligator sub index)"

"Cracking index (PCC) = 0.6 X (Transverse sub index) + 0.4 X (Longitudinal sub index)"

The most used ride-quality indicator is the IRI. Based on the IRI obtained by the Iowa DOT and represented on a scale of 100, the riding index employed in this research. *"IRI data were interpreted as a perfect 100 for values below 0.5 m/km and as 0 for values beyond 4.0 m/km on the index scale. Using linear interpolation, further values between 0.5 and 4 m/km were determined"* (Hosseini et al., 2020).

A weighted average method was utilized to determine the PCI values after all cracking, riding, rutting, and faulting indices for AC, COM, and PCC pavements were computed. The following are the current formulas for computing the PCI for AC, COM, and PCC pavements

"PCI (PCC) = 0.4 X (Cracking Index) + 0.4 X (Riding Index) +0.2 X (Faulting Index)"

"PCI (COM)=0.4 X (Cracking Index) +0.4 X (Riding Index) + 0.2 X.(Rutting Index)"

"PCI (AC) = 0.4 X (Cracking Index) +0.4 X (Riding Index) +0.2 X (Rutting Index)"

The lowa DOT rates the pavement condition of the interstate highway system as good based on PCI values. According to these classifications, up until the end of 2017, 91 percent and 79 percent, respectively, of the interstate highway system and the non-interstate highway system in the state of Louisiana were categorized as having good condition pavement. This is based on PCI values between 76 and 100, fair, between 51 and 75, and poor, between 0 and 50. (Hosseini et al., 2020).

2.6.6 Relation between riding index and IRI

Equation is used by the lowa DOT to convert the IRI data as it determines the riding index (Alharbi, 2018)

$$Riding\ index = \frac{IRI\ value - 253}{32 - 253}\ X\ 100$$

The riding index is measured on a scale of 0 to 100, with 100 representing ideal riding. *"All IRI values below 32 (in./mile) are regarded as 100 on the Iowa DOT ride index scale, while all values over 32 are regarded as 0.253 (in/mile) is equivalent to 0"*

2.6.7 Relation between PCI and IRI case study of St. John's City

PCI and IRI data were gathered and extracted using the application "DataPave." Road segments from several different climatic zones, including the *"Province of Quebec, Ontario, Prince Edward Island, State of New Jersey, New York, Maryland, Virginia, and Vermont"*, were included in the test locations. However, as the Province of Newfoundland and Labrador has particular meteorological characteristics, no test section was taken into consideration there. Equation represents the study's basic model that links PCI and IRI (Ali et al., 2019).

"Log (PCI)=2 – 0.4361Log (IRI)"

Regression model to forecast PCI from IRI data

*"PCI=81.890 - 11.037*IRI"*

The correlation coefficient (R^2) of this relationship is 0.79.

2.6.8 Relation between PCI and IRI for LTPP and MTO Roads

The relationships being developed highly depend upon the data being used. This section of the literature review will try to establish understanding that the database has an equal weightage while developing the relationships as that of relationships development technique. The data then eventually belong to specific area or region with certain traffic, climate and temperature conditions. The co-efficient of determinations R^2 mentioned in this section are of keen importance.

2.6.8.1 IRI versus PCI for LTPP Road Sections

The IRI data points and PCI values were plotted. The following equation represents the fitted regression line. The resultant R2 seems to be somewhat low when compared to some of the findings from earlier studies, although it is still greater than some of the reported numbers. However, it is important to keep in mind that the data was gathered throughout a wide geographic region, including 61 provinces, states, and territories. Furthermore, this information was obtained over a 26-year span. This indicates that material was gathered using multiple surveyors, agencies, and technological platforms in a variety of environmental settings (Piryonesi et al., 2021).

$$IRI = -0.012PCI + 2.064,\ R^2 = 0.302$$

Where R^2 is the coefficient of determination.

2.6.8.2 IRI Versus PCI for MTO roads in 2014

The data of Ontario provincial roads gathered by the Ontario Ministry of Transportation (MTO) was also studied in order to demonstrate how the variance in the data can significantly affect the correlation between the PCI and IRI. Only the 2014-collected statistics for asphalt roadways were extracted and compiled for this particular use (Piryonesi et al., 2021).

$$IRI = -0.045PCI + 5.024,\ R^2 = 0.697$$

2.6.9 PCI relationship with IRI on flexible pavement

The arterial road stretch of Medan City's inner ring road was the subject of the case study that was chosen. The functioning conditions of PCI and IRI are different, according to the analysis's findings. These two factors are used to create an exponential regression equation (Hasibuan et al., 2019).

$$\text{IRI} = 16.07\exp^{-0.26\text{PCI}}$$

According to the value of the coefficient of determination, there is a significant correlation between PCI and IRI. Since the correlation between these two factors is substantial but in the opposite direction, the R-value of -0.768 shows that 59.0% of the PCI value has an IRI value (Hasibuan et al., 2019).

2.7 Relationship with Resilient Modulus

The pavement structural assessment, which is thought to be a good approach for determining the state of the pavement layers and the need for restoration, has a workable solution described in this research. By utilizing ANN and regression models, a relationship is established between the deflection bowl parameters obtained from FWD and two pavement performance indices, the IRI and the PASER. Project field surveys are carried out from 318 sections of the major highways in the Iranian provinces of Kermanshah and Ilam in order to gather the necessary data. The findings demonstrate that the model satisfactorily correlates structural indices based on deflection measurements like IRI, PASER, and PASER. The performance of ANNs compared to non-intelligent models is much better when results from regression and ANN models are compared. The results of this research show that correct structural pavement assessment is achieved by combining the IRI and PASER indices (Fakhri & Shahni Dezfoulian, 2019a).

The pavement structural evaluation parameter, which is most often utilized in this study, is one of several. While the Base Layer Index (BLI) and Middle Layer Index (MLI) both indicate the state of the base layer and subbase layer, the radius of curvature (ROC) is more representative of the surface (asphalt) and base layer. Additionally, the structural response of the subgrade is reflected by the Lower Layer Index (LLI).

In fact, three degrees of sound, warning, and severe were recommended for the assessment criterion for pavement layers. The table below illustrates the relationship between structural factors and assessment strategy.

Table 2-3 Pavement structural condition assessment

Structural condition evaluation	Structural indices range			
	ROC	**BLI**	**MLI**	**LLI**
Sound	>100	<200	<100	<50
Warning	50 to 100	200 to 400	100 to 200	50 t0 100
Severe	<50	>400	>200	>100

2.7.1.1 Correlation between IRI and structural indices

The authors employed regression and ANN models to examine the connection between structural indices, roughness, and surface distress. To do this, the structural parameters were initially estimated using IRI alone, and then IRI and PASER indices were taken into account together. The regression equations between structural indices and IRI_R are shown in the following table. As a consequence, it is not always preferable to estimate all structural indices (*"ROC, BLI, MLI, and LLI"*) using simply the IRI index. Additionally, the R2 value for the two ROC and BLI indices is not very high and might be increased. The R2 value for the MLI is unacceptable, and the R2 computation is not directly relevant to the LLI index (Fakhri & Shahni Dezfoulian, 2019a).

Table 2-4 Evaluation of structural indices from IRI_R data

Input Variable	**Equation**	**R^2**	**Output Variable**
IRI_R	$ROC = 772.33\ (IRI_R)^{-1.696}$	0.74	Radius of Curvature (ROC)
IRI_R	$BLI = 85.806\ (IRI_R) - 75.754$	0.78	Base Layer Index (BLI)
IRI_R	$MLI = 15.997\ (IRI_R) + 42.502$	0.273	Middle Layer Index (MLI)
IRI_R	-	-	Lower Layer Index (LLI)

2.7.1.2 Correlation between IRI and PASER

It is possible for the state of the pavement layers to result in distresses such roughness, rutting, alligator cracks, transverse cracks, and longitudinal cracks. The PASER index and IRI are taken into consideration while developing the current models. The R2 values for the ROC, BLI, MLI, and LLI have improved to some extent as a result of the employment of both IRI and PASER indices, as shown in the accompanying table, along with a low MSE and a random distribution of residuals. *"When a polynomial linear model is used for the ROC index instead of a non-linear power model, R2 rises by 5%. According to the findings of the linear model, the R2 for the BLI index has increased by 7%."* Although R2 has changed noticeably and the MSE for the MLI and LLI indices is low, the value of R2 is insufficient to accurately determine structural indices (Fakhri & Shahni Dezfoulian, 2019a).

Table 2-5 Simple linear and polynomial linear model results

Input Variables	Equation	R^2	Output Variable
X=IRI_R Y = PASER	*"Z = 164.4 – 107.7X + 25.9Y + 67-52X2 + 17.4XY – 12.05X^3 – 5.318X^2Y"*	0.77	Z = ROC
X= IRI_R Y = PASER	*"Z = 147.9 + 62.47X – 32.15Y"*	0.84	Z = BLI
X= IRI_R Y = PASER	*"Z = 81.88 - 4.854X - 25.52Y"*	0.47	Z = MLI
X= IRI_R Y = PASER	*"Z = 34.29 - 6.876X - 7.593Y"*	0.13	Z = LLI

2.7.2 Relationship between rutting, IRI, and Mr of flexible pavement

This research looked at the link between flexible expressway pavement's robust modulus, rutting, and roughness. From mile 17.90 to km 52.20 on the Shah Alam Expressway, an assessment was undertaken. The expressway had three lanes in either direction (*"slow, middle and fast lanes"*). The complete test section's roughness and rutting were assessed using the scanning vehicle. While using a falling weight deflectometer, the resilient modulus values for the *"bituminous layer (E1), road base (E2), and subgrade (E3)"*. This research found that the resilient modulus (MR), roughness, and rutting do not correlate well (Noor et al., 2019).

2.7.2.1 Correlation of Resilient Modulus with Roughness

Poor correlations were found in the regression study between the resilient modulus (E1), (E2), and (E3) and Roughness (IRI) for the slow lane *("R2 = 0.0104, R2 = 0.002, and R2 = 0.0025," respectively)*. Poor correlations *("R2 = 1E-09, R2 = 0.008, and R2 = 0.006")* for regression analysis were also produced by the resilient modulus (E1), (E2), and (E3) and roughness for middle lane. R2 values for the fast lane *("0.035, 0.042, and 0.094")* also showed poor correlation (Noor et al., 2019).

Table 2-6 Correlation of Resilient Modulus with Roughness based on layers and lane

Layers	Lane	R^2
Bituminous layer (E1) Base layer (E2) Subgrade layer (E3)	Slow lane	For E1; R2 = 0.0104 For E2; R2 = 0.0020 For E3; R2 = 0.0025
	Middle lane	For E1; R2 = 1E-09 For E2; R2 = 0.008 For E3; R2 = 0.006
	Fast lane	For E1; R2 = 0.035 For E2; R2 = 0.042 For E3; R2 = 0.094

2.7.2.2 Correlation of Resilient Modulus with Rutting

Poor correlations were found in the regression study on the resilient modulus (E1), (E2), and (E3) and Rutting for the slow lane *("R2 = 0.013, R2 = 0.1399, and R2 = 0.00895")*. Poor correlations *("R2 = 0.0263, R2 = 0.0668, and R2 = 0.0089")* for regression analysis were likewise produced by the resilient moduli (E1, E2, and E3) and rutting for the middle lane. *"R2=0.0003, R2=0.0113, and R2=0.0104"* similarly showed a low correlation for the fast lane (Noor et al., 2019).

Table 2-7 Correlation of Resilient Modulus with Rutting based on layers and lane

Layers	Lane	R^2
Bituminous layer (E1) Base layer (E2) Subgrade layer (E3)	Slow lane	For E1; R2 = 0.013 For E2; R2 = 0.1399 For E3; R2 = 0.00895
	Middle lane	For E1; R2 = 0.0263 For E2; R2 = 0.0668 For E3; R2 = 0.0089
	Fast lane	For E1; R2 = 0.0003 For E2; R2 = 0.0113 For E3; R2 = 0.0104

2.7.3 Effect of pavement age on Resilient Modulus

Asphalt oxidation causes the hot mix asphalt (HMA) mixture to age-harden. The ageing process causes the asphalt in HMA to harden, which enhances the stiffness of the mixture. The main causes of hardening or stiffening are the increasing oxidation of the in-place material in the field and the loss of volatiles in asphalt during the building phase. Both elements enhanced the viscosity of asphalt, which made the mixes stiffer as a result. Basically, during the course of its service life, asphalt has two distinct ageing processes. During the manufacture of HMA, it is exposed to high temperatures and a high level of air exposure (short term aging). Then, it is exposed to the environment as in-service pavement for an extended period of time at a somewhat lower temperature (long term aging). Asphalt therefore becomes harder with both short-term and long-term ageing. Because so many variables affect how quickly we age, both short-term and long-term ageing are very complicated phenomena. Since stiffer mixtures have better load distribution properties and are more resistant to permanent deformation, ageing may be advantageous. However, it may also lead to embrittlement, which increases the likelihood of cracking and reduces durability in terms of resistance to wear. Aged HMA mixtures can cause a variety of distresses, including fatigue and thermal crack (Idham et al., 2013).

The asphalt binder's viscosity increased when the mixture was exposed to a lower temperature, which decreased its strain and flow ability. The resilient modulus is higher as a result. On the other hand, the strain and mixture flow ability increased when the same sample was subjected to higher temperatures because the asphalt binder became less viscous and its resilience modulus fell. Consequently, the resilience modulus dropped as the temperature rose (Idham et al., 2013).

The performance of this combination throughout the service life of the pavement may be determined by the artificial ageing procedure applied to the mixes. Before beginning any pavement maintenance or rehabilitation, it can be used as a preliminary indicator of the condition of the pavement (Idham et al., 2013).

2.7.4 Effect of loading frequency on Resilient Modulus

Increasing the load cycle frequency causes a slight increase in the resilient modulus. Higher resilient modulus values derive from shorter rest intervals and quicker strain recovery times caused by a higher load cycle frequency (Fakhri & Ali Reza, 2014).

$$\text{“}Log(Mr) = a \log(f) + b\text{”}$$

Mr is the resilient modulus (MPa), f is the loading frequency (Hz), “a” and “b” are the model's constant coefficients. Positive values for "a" and "b" show that the resilient modulus was evaluated more favorably as the loading frequency increased. The two main factors that regulate the balance between fatigue and rutting lifetimes are base thickness and subgrade resilient modulus. Trucks that violate the law should be unloaded when their weights surpass specific restrictions since tensile and compressive strain rose with rising axle loads and dropped with increasing asphalt layer modulus (Behiry, 2012).

2.8 Summary

This chapter provides in-depth literature review about the relationships developed by the researchers for PMS. It establishes an understanding that the relationships are dependent upon the variables being used, pavement data, and the region from where the pavement data belongs. It also states that the pavement condition indices can have both good and poor relationships with the pavement structural condition assessment parameters. This chapter provides basis of the research study undertaken by the author and gives an oversight of the practices carried out by the researchers so far.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The study is planned around the objectives and methods for achieving them, which are outlined in this section. The literature review, data collection and analysis would be used to determine the degree of study, type of research activity, research focus, and factor deployment. The research methods will be chosen with the intention of creating a relation between data collection and development of relationships (Alsanad, 2015). After researching the suitable approach for this form of study, this research will be managed by the back calculation of Mr. In the related section, the data interpretation and findings are further discussed.

The methodologies and processes for research work are described in this chapter. As previously stated, the primary goal of this research is to develop the relationships between IRI, PCI, and Resilient Modulus (back calculated from FWD) using LTPP database and to validate the relationships using data obtained from Pakistan Motorways M2. As a result, the goals of this portion of the report are to identify the truly representative data to develop the relationships and equations. ASTM method for PCI determination is lengthy and hectic for large data set. Therefore, literature study is carried out and IRI and PCI relationships are adopted to determine PCI.

3.2 Research sites

This research is conducted on the motorways, M2, in Pakistan. M2, 367 km in length, starting from country's capital Islamabad to Lahore, which is the Provincial Capital of Punjab. These roads are included in the category of Motorway under the management of the National Highways and Motorway Police (NHMP), Pakistan.

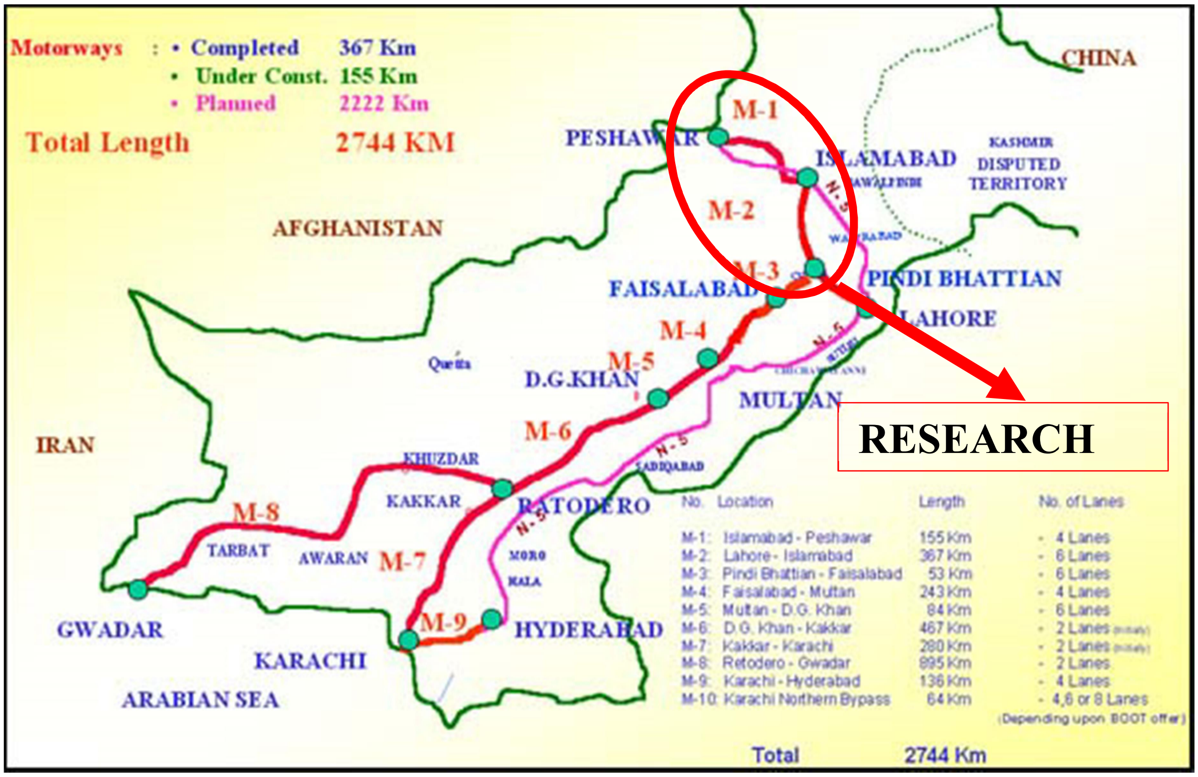

Figure 3-1 Location of research on M2 Pakistan

3.3 PCI Determination Method – Standard Method

Visually examining the pavement's surface might provide important details. Visual inspection data may be used to estimate repair amounts, assess the effectiveness of various M&R procedures and materials, assess the existing pavement state, forecast future pavement performance, and identify and prioritize pavement M&R (Maintenance and Rehabilitation) requirements (Karim et al., 2016).

The accepted technique (ASTM-D6433, 2009) used to calculate PCI Visible indicators of deterioration are noted and examined during a PCI survey. The final PCI rating is a number between 0 and 100, with 100 denoting a perfectly sound pavement. The pavement condition rating is derived from a correlation that, as shown in the graph below, plots the pavement condition rating as a function of the PCI value.

Table 3-1 PCI Rating (ASTM-D6433, 2009)

PCI	Rating
85–100	Excellent
70–85	Very good
55–70	Good
40–55	Fair
25–40	Poor
10–25	Very poor
00–10	Failed

3.4 IRI Determination Method – Standard Method

One of the criteria used to assess the serviceability level of road segments that may have an impact on the riding experience is the IRI. Good roads should be sturdy, level, waterproof, long-lasting, and cost-effective during their intended lifespan. As a result, roads should be periodically/regularly checked over and examined to determine the best course of action for restoration. Road roughness index may be calculated using (ASTM E1926, 2021), which is highly recommended (Hasanuddin et al., 2018). The index calculates the number of meters per kilometer that a laser placed on a customized van leaps as it travels down a road to represent pavement roughness in wheel path. The smoother the ride seems to a road user, the lower the IRI rating at a given speed.

The scale for the IRI is illustrated below. *"IRI is helpful in evaluating the overall ride quality of pavement; a higher IRI score indicates a rougher road surface"* (MDOT, 2017).

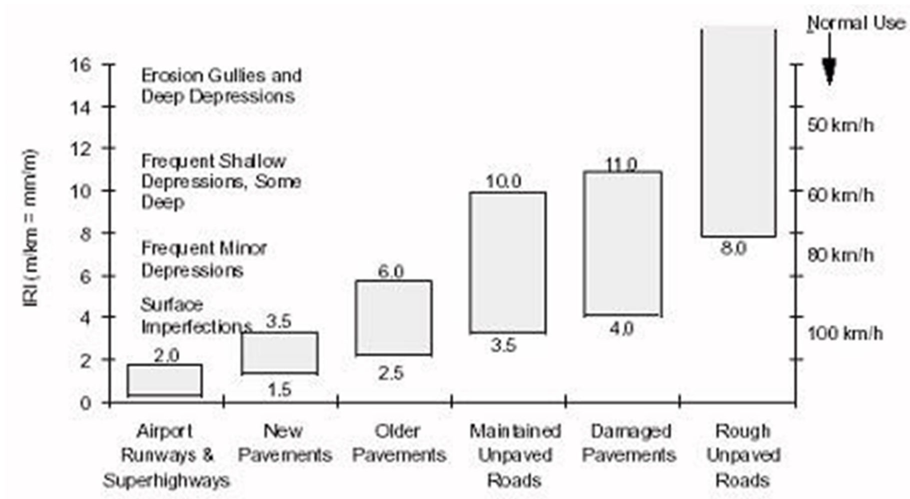

Figure 3-2 IRI roughness scale (Pavement Interactive, 2022)

3.5 Determination of FWD back calculated Resilient Modulus – Standard Method

Information on the performance of pavement structure under traffic load and environmental conditions is included in evaluation. The ability of a road's pavement to withstand the weight of traffic is referred to as its structural capacity. It often follows an analysis of the mechanical characteristics of each layer of the pavement construction, including elastic modulus, fatigue characteristics, and deflection condition, as determined by laboratory experiments or on-site non-destructive (NDT) testing. The FWD is an NDT technique (Hasanuddin et al., 2018). To evaluate the vertical deflection response of a surface to an impulse load, one uses FWD. The pavement surface feature is captured using precise load measurement and deflection sensors, which is utilized to compute pavement parameters such (PaveTesting, 2022)

- *"Bearing Capacity"*
- *"Layer Thickness"*
- *"E Moduli"*
- *"Expected Surface Life"*

The loading plate should be positioned over the preferred test area according to the standard procedure (ASTM D4694, 2015) used to assess the stiffness of the road. The FWD technique simulates the size and duration of a single heavy moving wheel load by applying dynamic stresses to a pavement surface. As shown in the illustration below, the maximum deflections at each measurement site are noted in micrometers.

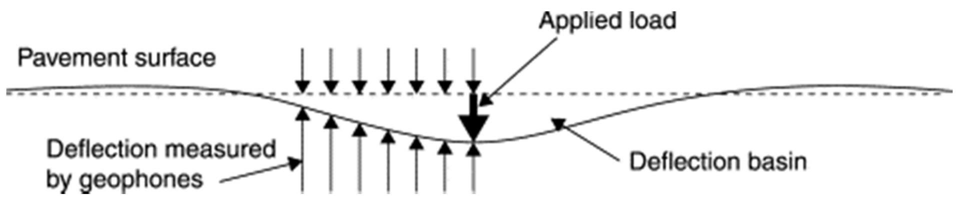

Figure 3-3 Schematic of FWD load and deflection measurement

Transducers would measure the deflected surface basin after loading. Geophones and seismometers are often utilized as transducers in FWDs for a variety of purposes. Deflection sensors must be placed closer to the load center on pavements with thin asphalt layers than they would be on pavements with larger asphalt layers. The procedure assesses how the surface responds vertically to an impulse load delivered to the pavement surface (Wang & Birken, 2014).

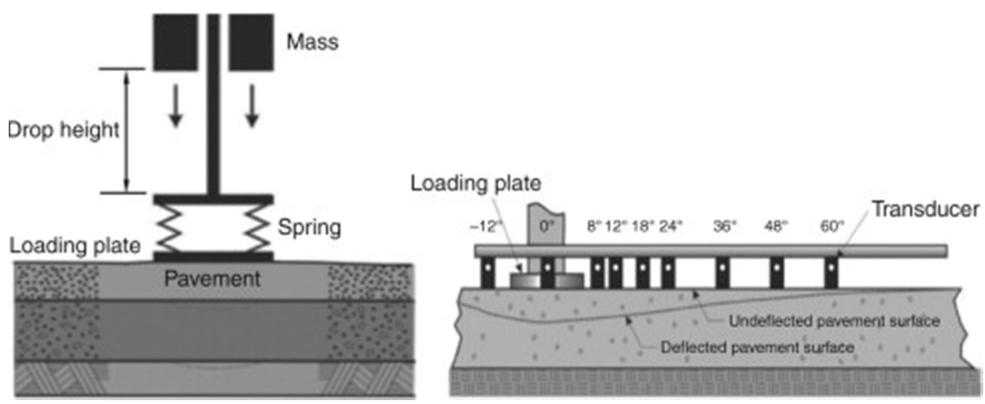

Figure 3-4 Diagram of the FWD testing (Wang & Birken, 2014)

3.6 Data Acquisition FROM INFOPAVE

Following checks/filters are applied for data acquisition from https://infopave.fhwa.dot.gov/.

3.6.1 Experiment Type

Following experiment types are selected for the acquisition of data.

1. *"GPS 1: Asphalt Concrete on unbound granular base"*
2. *"GPS 2: Asphalt Concrete on bound base"*
3. *"GPS 6: Asphalt Concrete overlay of AC pavement"*
4. *"SPS 1: Strategic Study of Structural Factors for Flexible Pavements, New/Reconstructed AC pavements"*
5. *"SPS 3: Preventive Maintenance of AC Pavement"*
6. *"SPS 5: AC Overlay of AC pavement"*

3.6.2 Climatic Regions

Data belongs to following climatic regions of the United States.

1. Dry, No freeze
2. Wet, No freeze

3.6.3 Temperature

Temperature ranges from 20^{o} C to 30^{o} C (Average Annual Mean Temperature) during LTPP monitoring period. According to world bank climatology report 2021, Pakistan's temperature is above 20^{o}C.

3.6.4 Total Number of Sections

Total Number of sections is 193. Each section has a length of 154 m with 3.6 m width. The data prominently belongs to Texas, Florida, and Arizona.

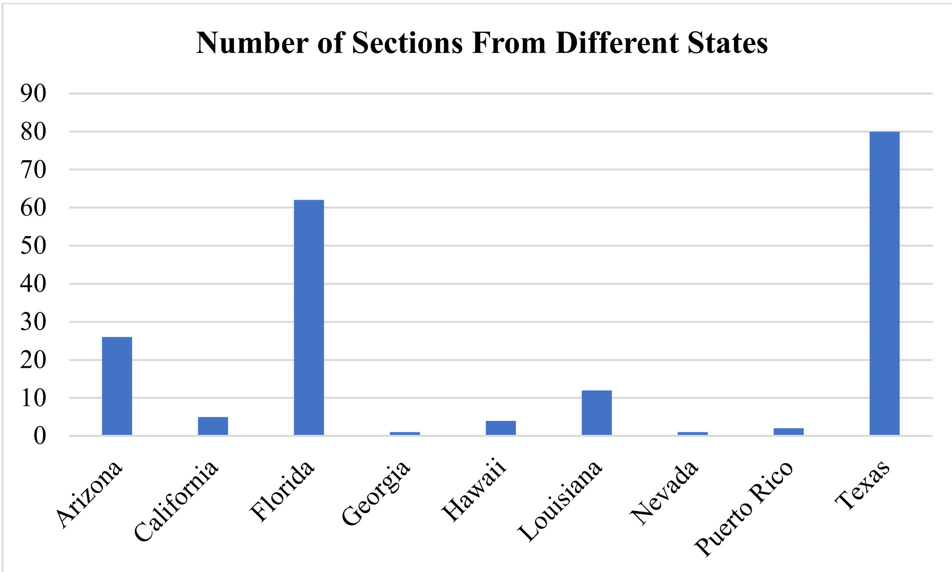

Figure 3-5(Number of LTPP sections from different states)

3.7 Working methodology

The IRI was already available in LTPP database but data of PCI was not in LTTP database. So the determination of PCI was nearly impossible for such huge data set using ASTM methodology, total 193 sections and different data for different years. Every equation in the literature was not applicable because significant percentages of values were more than 100. Some values were in negative and not representing truly. However, PCI is determined by using the relationship between IRI and PCI. MEPDG distresses were available but ASTM method for PCI determination is lengthy and hectic for large data set. Therefore, literature study is carried out and IRI and PCI relationships are adopted to determine PCI.

3.7.1 Issues

Any PCI-IRI based equation cannot be used to determine PCI. PCI determined from numerous equations had following issues;

1- PCI values obtained from some equations resulted in PCI values less than zero or more than 100, therefore that values and equations are discarded.
2- PCI values obtained from some equations were not representing the true relationship between IRI and PCI. Factually, PCI should be approaching 100 if IRI is approaching zero.

Therefore, the equations are adopted on the basis of their justifiable output and any equation which gives justifiable output can be used to determine PCI using any variable.

3.7.2 Multiple linear regression

Multi-linear regression models are those that include one dependent variable and many independent variables (Uyanık & Güler, 2013). Resilient Modulus and IRI are independent variables in this study, whereas PCI is a dependent variable. In this work, the PCI value is predicted using the multiple linear regression approach, and the PCI, Mr, and IRI are related using this technique as well.

The researcher may include all of these potentially significant components into one model by using multiple linear regressions. The benefits of this strategy are that it could result in a more exact and detailed knowledge of how each individual aspect is related to the outcome. Additionally, it provides insight into the relationships between the many predictor variables individually as well as the relationship between all of the components and the result as a whole (Marill & Lewis, 2004).

3.7.3 Available Data of M-2

Following data is retrieved from the design report of M-2, 2014 (Modernization and Overlay of Lahore-Islamabad Motorway M-2 on BOT basis).

1. IRI
2. Back calculated Resilient Moduli of pavement layers
3. Structural Cracking Index
4. Thermal Cracking Index
5. Patching Index
6. Rut Depth
7. SN_{eff} and SN_o
8. Pavement layers' thickness
9. ESAL

3.7.4 PCI Determinations for M-2

PCI for M-2 is determined using (Bektas et al., 2014) and (Hosseini et al., 2020) approach:

$$PCI_{AC} = 0.40 * Cracking\ Index + 0.40 * (Riding\ Index) + 0.20 * (Rutting\ Index)$$

- Cracking Index data is provided by NHA.
- Rutting Index is determined using (Yu et al., 2017) and (Ghanbari et al., 2020) approaches:
  - **Rut Index**: If RUT_AVG ≤ 0.1, Rut Index = 100, If RUT_AVG ≥ 0.66, Rut Index = 0, otherwise $\boldsymbol{Rut\ Index = 100 - 178.57 * (RUT\_AVG) + 17.86}$ (Ghanbari et al., 2020)
  - **Rut Index**: also termed as $\boldsymbol{Rutting\ Depth\ Index = 100 - 2.0 * Rut\ Depth}$ for rut depth ≤ 20 mm. (Yu et al., 2017)

- (RD = 1.04 mm on M-2)
- If this approach is used, R^2 for validation comes 0.63

- Riding Index is determined using (Alharbi, 2018).
  - Riding Index = 100 if IRI < 32 (in/mile), Riding Index = 0 if IRI > 253, otherwise

    Riding index = $\frac{IRI-253}{32-2} * 100$

3.8 Summary

This chapter provides the research methodology adopted to determine the values of the selected variables and to determine the relationships between the variables. PCI for LTPP database is determined using equations between PCI and IRI. Only those equations are usable which give justifiable output. The relationships are then developed using LTPP database. The developed relationships are then validated with the 25% of the LTPP database. On the basis of statistical and regression indices depicting significant relationships between the variables, the relationships are then validated on M-2 data. The PCI is determined for M-2 using Bektas et al., Hossieni et al, and Iowa State University practices.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Pavement Condition Report of M-2

This chapter delineates the analysis and results of the retrieved data from National Highway Authority, NHA report. The various tests, IRI, PCI and FWT are performed by NHA on Motorway M2 in 2014 and their data are retrieved from the design report of 2014 for this research.. The complete analysis and results are done by using the data of M2 and their results are discussed in this section.

In order to evaluate the pavement roughness, IRI was tested by NHA in 2014. IRI results are calculated from the profile data along each wheel path and reported at 349 km in total distance with 1 km intervals. This IRI profile is plotted of south bound and north bound outer lanes. The abrupt rise in the plots for instance up to IRI of 6.5m/km at 225 km distance as this point is near to Kalar Kahar and this region has rigid pavement.

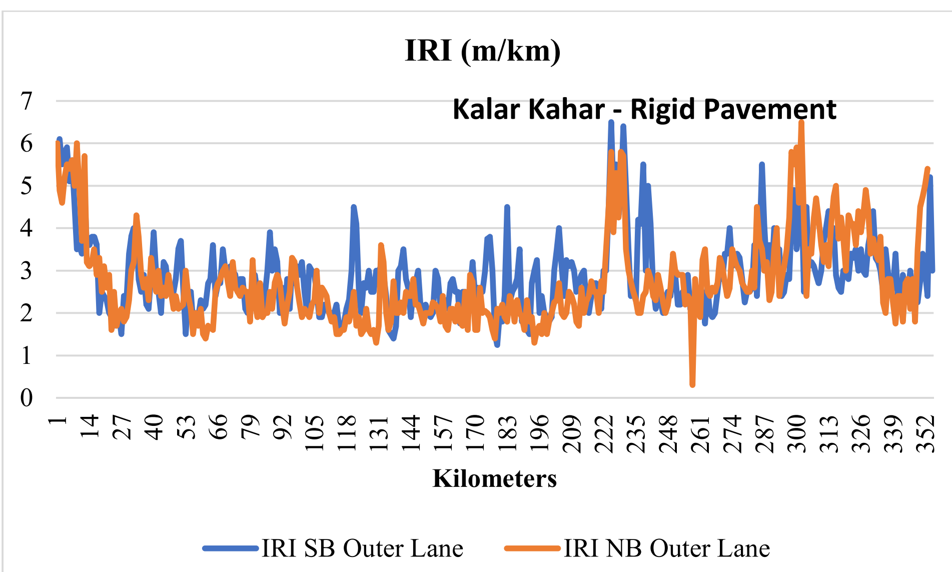

Figure 4-1 IRI (NHA, 2014)

The following figure is of rut depth of Motorway M2, south bound and north bound of outer lane. The rut depth is plotted of 351 km total distances with 1 km intervals. South bound outer lane has high value of rut depth as compared to north bound outer lane. Following figure shows a sudden increase or decrease in the pavement rutting with distance. The maximum value of rut depth of south bound outer lane is observed, 4.4 mm at 236 km as this region has road gradient so the movement of heavy traffic is slow and causing more rutting as compared to other region.

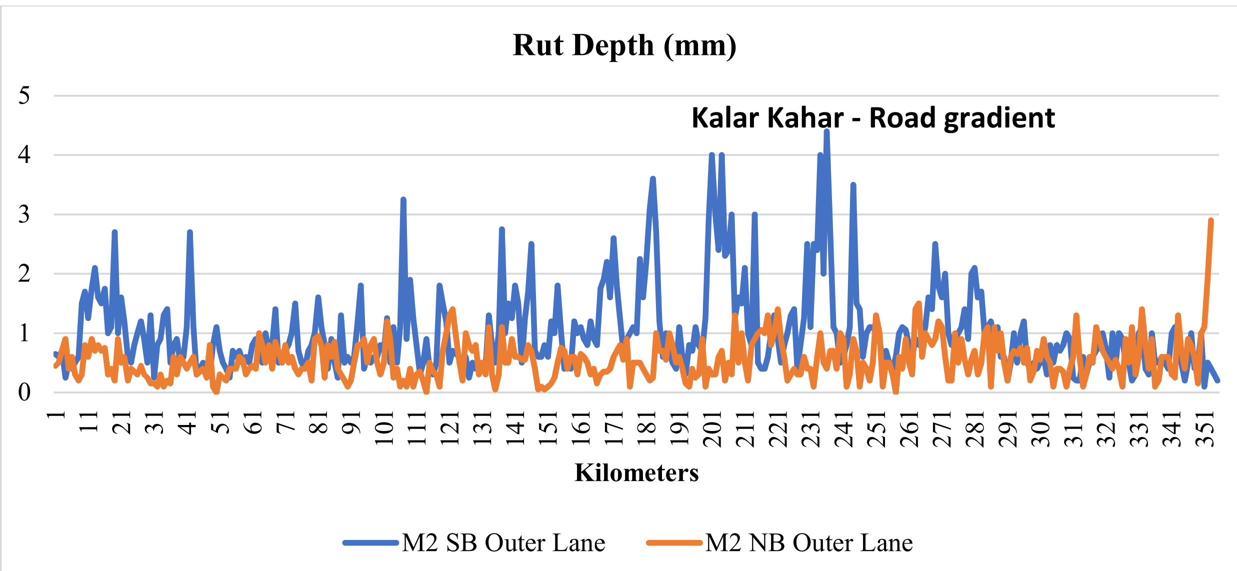

Figure 4-2 Rut Depth (NHA, 2014)

The following figure is of PCI of Motorway M2, south bound and north bound of outer lane. The PCI is plotted of 345 km total distances with 1 km intervals. South bound outer lane has low value of PCI as compared to north bound outer lane. Following figure shows a sudden increase or decrease with distance. The maximum value of PCI of north bound outer lane is observed, 99.76 mm at 258 km due to the section of rigid pavement. According to PCI scale (ASTM-D6433, 2009), pavement of M2 is good and no need of maintenance.

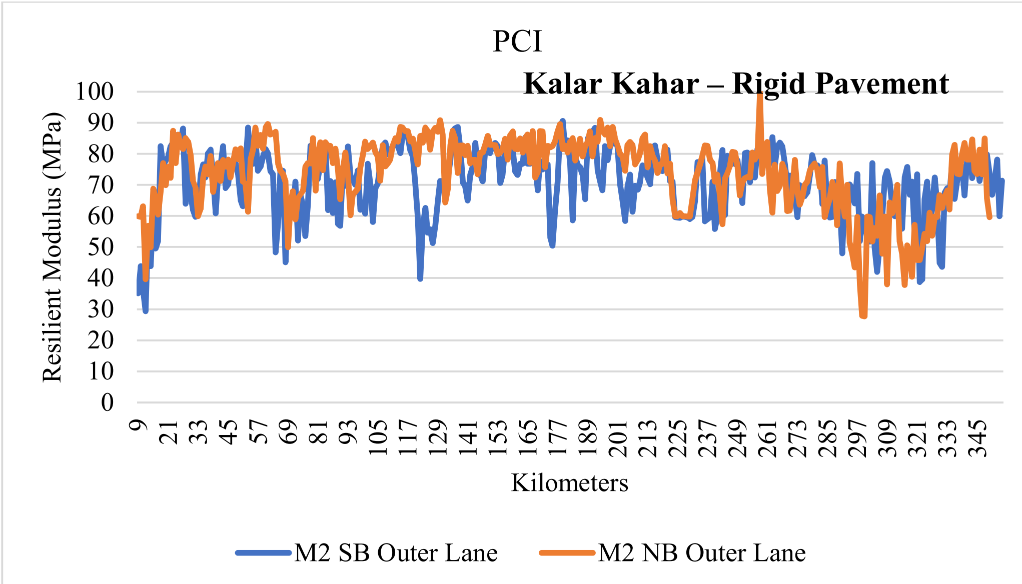

Figure 4-3 PCI (NHA, 2014)

4.2 Results

4.2.1 Development of Relationships b/w IRI, Mr (back calculated), and PCI

The equations developed on the basis of the given methodology are elaborated as under.

Following equation is used to determine PCI for LTPP data.

$PCI = -9.031 * IRI + 0.283 * (IRI^2) + 85.119$ (Abed, 2020)---------$R^2 = 0.71$

This equation has helped to determine following "significant" equations. Mr (MPa) and IRI (m/km)

For Asphalt Concrete Layer:

$PCI = 84.53 - 8.12\ (IRI) - 1.48\ x\ 10^{-6}(Mr)$ ------- $R^2 = 0.99$

Validation using M-2 data: $R^2 = 0.68$

Model validation using 25% of the LTPP data is shown as under. The relationships are giving satisfactory results in terms of their validation on LTPP database. Model validation for asphalt layer is developed between estimated PCI and actual PCI as shown in following figure. The primary goal of model validation is to compare the accuracy and performance of estimated data derived from an equation to actual data. This model can represent true condition.

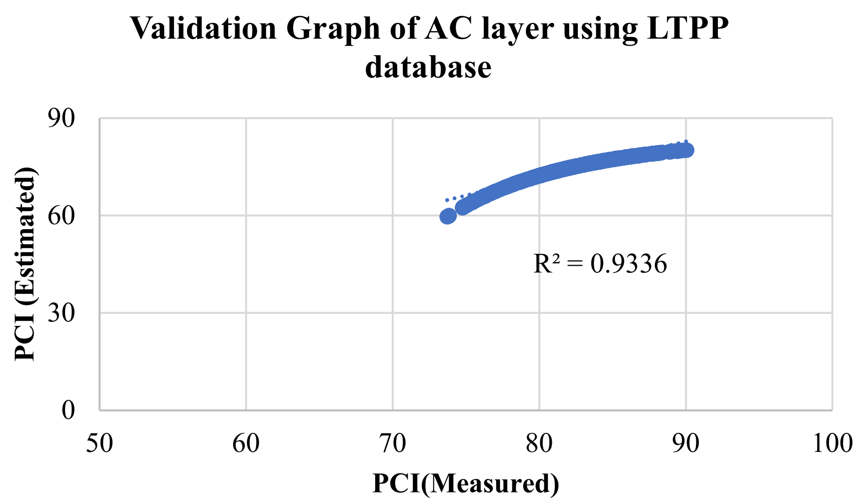

Figure 4-4Validation Graph of AC layer using LTPP database

The findings also indicate a satisfactory validation results when validated using M-2 database. Literature terms determination of coefficient as satisfactory if it is near 0.70. Therefore, it can be concluded that the developed equation using the practice stated above is giving satisfactory results.

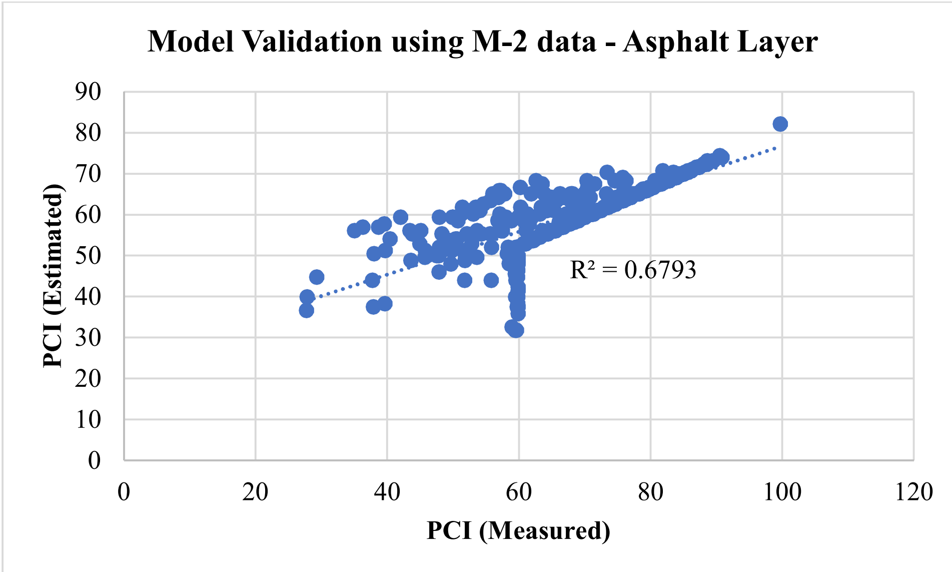

Figure 4-5 Model Validation using M-2 data- Asphalt Layer

For Base Course:

This equation is used to determine PCI; Log $(PCI) = -0.115 * Log\ (IRI) + 2.131$

The developed equation is as follows;

$$PCI = 91.987 - 7.29\ (IRI) - 3.35\ x\ 10^{-6}(Mr)$$ ------- $R^2 = 0.90$

Validation using M-2 data: $R^2 = 0.61$

Model validation for base course is developed between estimated PCI and actual PCI as shown in following figure. The main purpose of development of model validation is to check the accuracy and performance of estimated data, obtained from equation, with the actual data. This model can represent true condition.

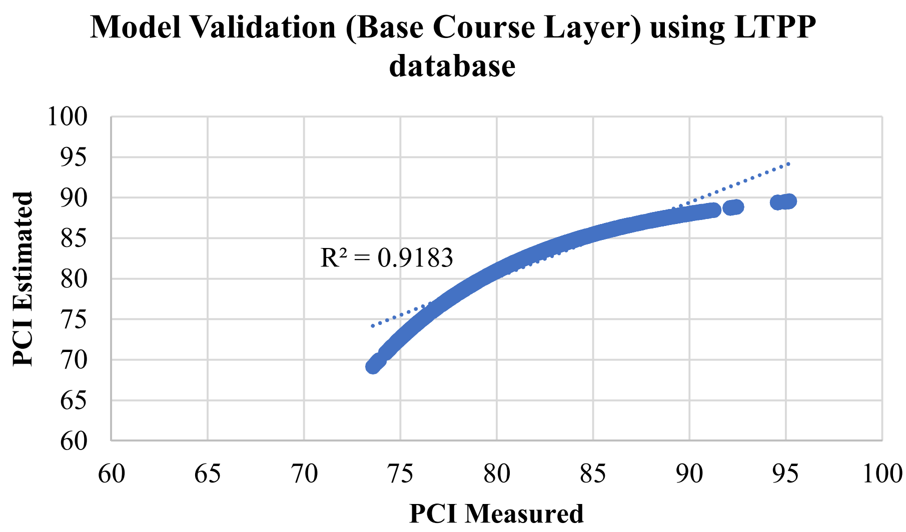

Figure 4-6 Model Validation (Base Course Layer) using LTPP database

The validation result pertaining to M-2 data is as under.

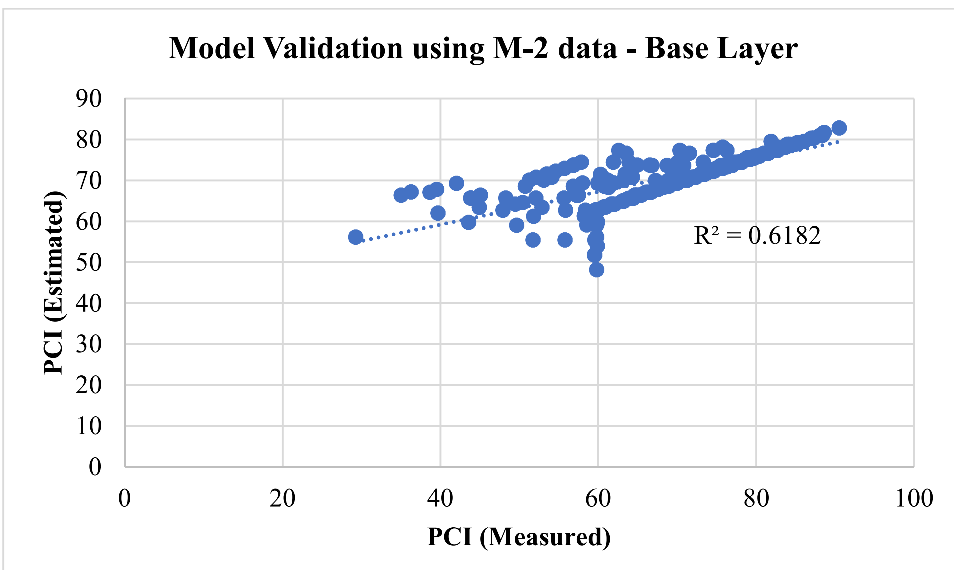

Figure 4-7 Model Validation using M-2 data- Base Layers

For Subgrade Layer:

$$PCI = 84.48 - 8.09\ (IRI) + 2.96\ x\ 10^{-5}(Mr) \text{ ------- } R^2 = 0.99$$

Validation using M-2 data: $R^2 = 0.68$

Model validation for subgrade layer is developed between estimated PCI and actual PCI as shown in following figure. The primary goal of model validation is to compare the accuracy and performance of estimated data derived from an equation to actual data. This model can represent true condition.

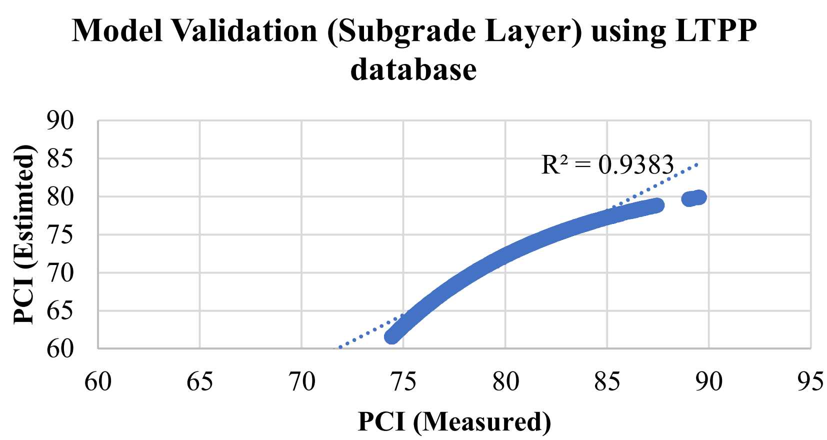

Figure 4-8 Model Validation (Subgrade Layer) using LTPP database

The validation result pertaining to the subgrade layer using M-2 data is as under. The models are significantly representing satisfactory validation results. The trend obtained is developing the perception that the adopted methodology is adoptable.

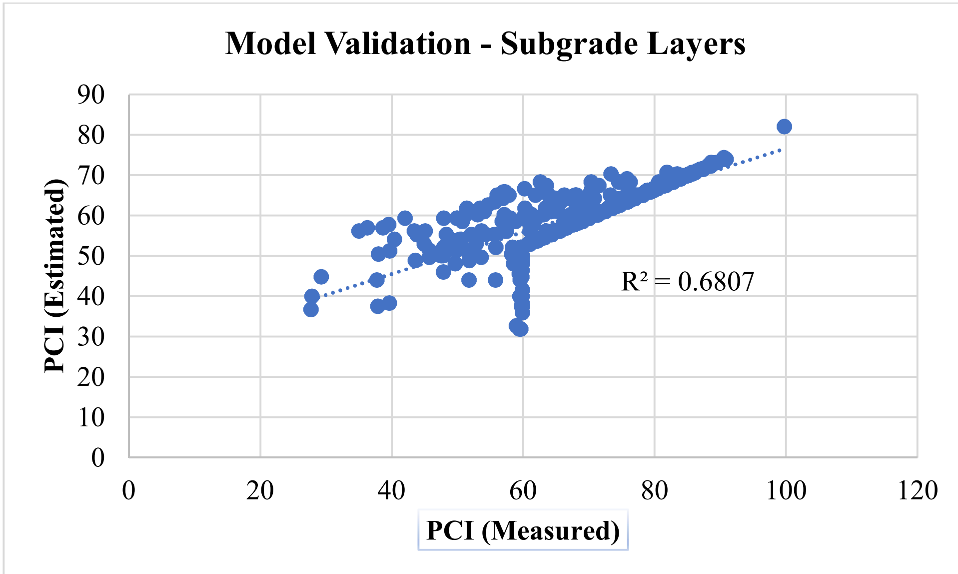

Figure 4-9 Model Validation using M-2 data- Subgrade Layers

4.3 Analysis

The following figures are of estimated PCI and actual PCI of Motorway M2, including south bound of outer lane. In this graph, both PCI values are plotted of 349 km total distances with 1 km intervals. Actual PCI of south bound outer lane has high value as compared to estimated PCI value of south bound outer lane. Following figures shows that the developed model underreports the actual PCI by a margin of almost 10 units.

Similarly, actual PCI of north bound outer lane has high value as compared to estimated PCI value of north bound outer lane. The results reveal that the maximum value of actual PCI of south bound outer lane is observed, 99.76 mm at 258 km and estimated PCI at same kilometer mark is 82.1 mm.

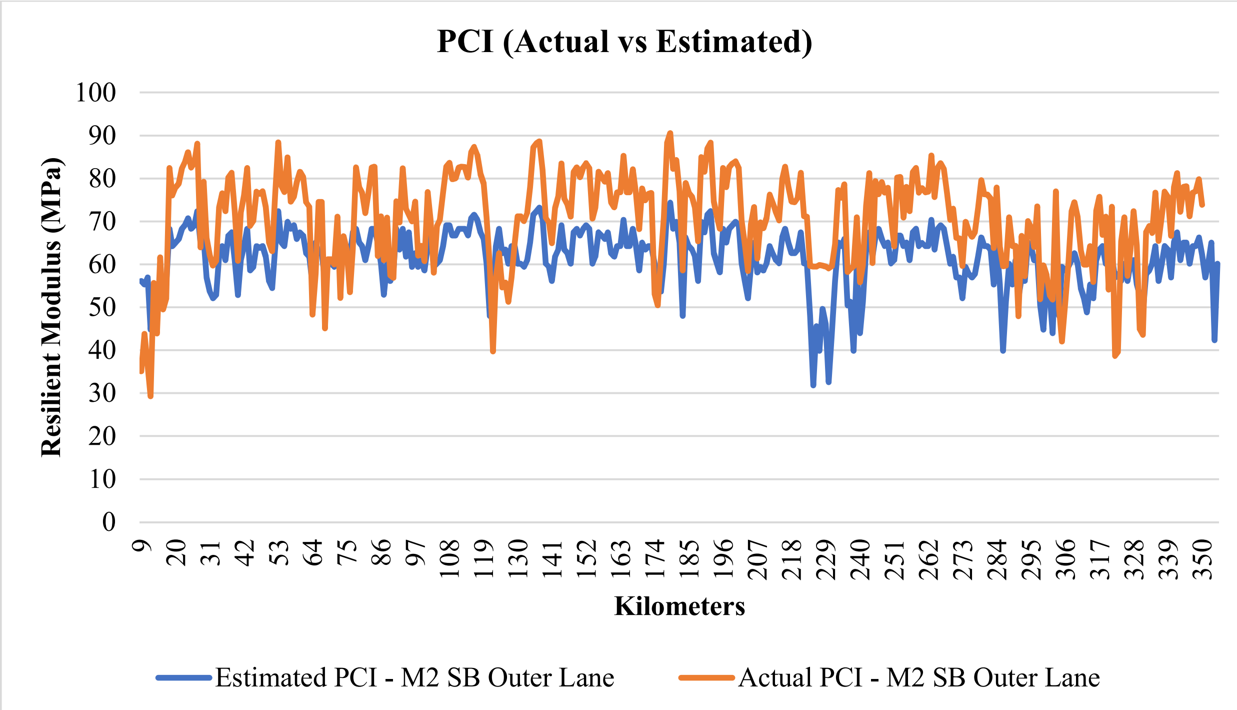

Figure 4-10 PCI (Actual vs Estimated) (NHA, 2014)

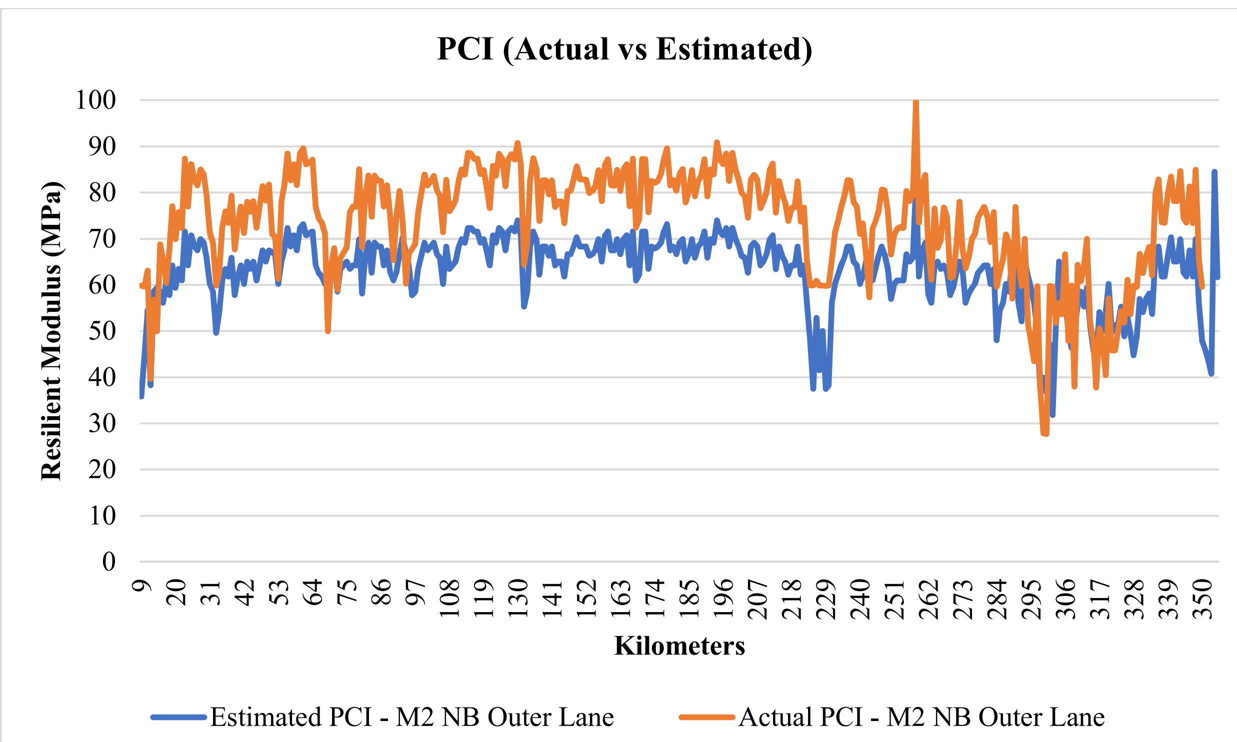

Figure 4-11 PCI (Actual vs Estimated) (NHA, 2014)

For all parameters deriving from the equations, t-statistics and P-values are evaluated in addition to R^2 values. The coefficients, standard errors, t-statistics, P-values (at a 0.05 significance level), and confidence intervals for the slope and intercept are included in the tables below (both upper limit and lower limit). The P-values are clearly less than 0.05 (Significance level). It indicates that the t-statistics are far into the critical zone, indicating that a sufficient evidence to discard the null hypothesis (at a significance threshold of 0.05) and finally conclude that there is a relationship between the Mr, IRI, and PCI.

The detailed regression tables with clear statistical and regression indices are attached herewith for further information and understanding.

4.4 Summary

The results obtained using the methodology adopted and mentioned in chapter 3 has brought satisfactory results. The models have been developed successfully and validated using both LTPP database and M-2 database. The validation results pertaining to the LTPP database has provided coefficient of determination (R^2) above 0.90 for all three models and layers. Therefore, it is deduced that the models are applicable and relationships exists among the selected variables (i.e., PCI, IRI, and back calculated Resilient Modulus). With that, it can also be deduced that PCI can be adopted as pavement performance indicator in Pakistan as it represents both surface condition and structural condition of the pavement. It takes all the possible distresses into the account.

Table 4-1 Regression statistics of AC Layer

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99950632
R Square	0.999012884
Adjusted R Square	0.999012366
Standard Error	0.134336341
Observations	3815

AC-LAYER

$$PCI = 84.53 - 8.12\ (IRI) - 1.48\ x\ 10^{-6}(Mr)$$

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	69621.38	34810.69	1928971	0
Residual	3812	68.79231	0.018046		
Total	3814	69690.18			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	84.53200816	0.00541	15625.61	0	84.5214017	84.54261462	84.5214017	84.54261462
IRI	-8.121772585	0.004486	-1810.62	0	-8.130567074	-8.112978097	-8.130567074	-8.112978097
Mr in MPa	-1.48563E-06	2.89E-07	-5.14936	2.75E-07	-2.05127E-06	-9.19985E-07	-2.05127E-06	-9.19985E-07

Table 4-2 Regression statistics of Base Layer

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.950793245
R Square	0.904007795
Adjusted R Square	0.903968446
Standard Error	1.223965405
Observations	4882

BASE-LAYER

$$PCI = 91.987 - 7.29\ (IRI) - 3.35\ x\ 10^{-5}(Mr)$$

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	68834.36514	34417.18257	22974.02188	0
Residual	4879	7309.18751	1.498091312		
Total	4881	76143.55265			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	91.98727143	0.043598858	2109.855051	0	91.90179803	92.07274483	91.90179803	92.07274483
IRI	-7.298866451	0.034191611	-213.4695123	0	-7.365897406	-7.231835497	-7.365897406	-7.231835497
MR in Mpa	-3.34939E-05	7.89439E-06	-4.242743761	2.24897E-05	-4.89705E-05	-1.80173E-05	-4.89705E-05	-1.80173E-05

Table 4-3 Regression statistics of Subgrade Layer

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999376231
R Square	0.998752852
Adjusted R Square	0.998752264
Standard Error	0.149880246
Observations	4250

Subgrade Layers

$$PCI = 84.48 - 8.09\ (IRI) + 2.96\ x\ 10^{-5}(Mr)$$

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	76403.09083	38201.54542	1700560.695	0
Residual	4247	95.40498252	0.022464088		
Total	4249	76498.49581			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	84.48226089	0.007597479	11119.77478	0	84.46736586	84.49715592	84.46736586	84.49715592
IRI	-8.097803009	0.004541204	-1783.184148	0	-8.106706143	-8.088899875	-8.106706143	-8.088899875
MR in MPa	2.96744E-05	1.18937E-05	2.494973763	0.012634334	6.35658E-06	5.29922E-05	6.35658E-06	5.29922E-05

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Database was retrieved by NHA design report, 2014 for this research. And this research shows the relationship between PCI, back calculated resilient modulus and IRI and also reveals their model validation to compare the accuracy and performance of estimated data derived from an equation to actual data. At the end, estimated PCI and actual PCI of Motorway M2 are compared for both south bound and north bound outer lane. This section is divided into conclusions and recommendations derived from this whole research.

5.1 Important Points from M-2 data

The following points are related to the M-2 database.

1. The abrupt rise of IRI reaches at 6.5 m/km near 225 km distance as this point is near to Kalar Kahar and this region has rigid pavement. According to IRI roughness scale, pavement of M2 is older but no need to maintenance.
2. The maximum value of rut depth of south bound outer lane at M2 is observed, 4.4 mm at 236 km as this region has road gradient so the movement of heavy traffic is slow and causing more rutting as compared to other region.
3. The maximum value of PCI of north bound outer lane of M2 is observed, 99.76 mm at 258 km due to the section of rigid pavement. According to PCI scale (ASTM-D6433, 2009), pavement of M2 is good and no need of maintenance.
4. The back calculated resilient modulus is determined for three layers; asphalt layer, base course layer and subgrade layer of motorway M2. Their back calculated Mr values are observed maximum at north bound outer lane, for asphalt layer 7219.5 MPa in between 214 km and 221 km, for base course layer 5952.9 MPa in between 243 km and 290 km,

and for subgrade layer, 662.6 MPa in between 225 km and 240 km. Their maximum values in these specific sections are due to rigid pavement near Kalar Kahar.

5.2 Conclusions

The points are stated as under.

1. Corresponding to the research objective # 1, the models are developed with statistical and regression indices showing that are equations are "Significant". The p-value for each variable is less than 0.05. t-stat value is either greater than +2 or less than -2, the Significance F values are 'zero'. These parameters show that the relationship exist between these variables with PCI being dependent variable on IRI and Mr.
    a. Model validation using LTPP database also shows satisfactory and justifiable results. The co-efficient of determination (R^2) is also above 0.90 that means the models can cover more than 90% variations in the data.
2. Corresponding to research objective #2, Model validation is developed between estimated PCI and actual PCI for three layers; asphalt layer, base course layer and subgrade layer of motorway M2 to compare the accuracy and performance of them. The findings indicate a satisfactory coefficient of determination R^2 of 0.68 for asphalt layer, 0.61 for base course layer and 0.68 for subgrade layer indicating a good model.
3. On the basis of developed models, the analysis is carried to know how good the models predict PCI condition of the pavement when compared with actual PCI. It is found out that the developed models underreport the actual PCI of the pavement by a margin of almost 10 units but the profile trend is similar to the actual PCI profile of the pavement.

5.3 Recommendations

1. Pavement management system (PMS) in data analysis is better method to assess the road conditions. NHA should also develop such database of each year on project level so that researches regarding pavement evaluation may increase in Pakistan.
2. The equations developed in this research must be considered as a bench mark and furthermore, with the help of these equations researcher can develop equations for any specific region, pavement section or motorways.
3. The equation can also be developed based on material characteristics. As different material used in road construction like aggregate, crumb rubber etc. have different PCI value, Mr value and behavior.
4. These equations give an idea that structural evaluation can be done by using the distress survey. Rutting starts from base or subgrade layer and fatigue cracking caused by tensile strain from the bottom of upper most layer (asphalt layer). So by using distresses survey, it can be easily found in which layer such types of fault occurred.
5. This planning is a network level planning and can help researcher to find the back calculated resilient modulus value after conducting survey distresses survey.
6. This research may help to decision makers to control the resilient modulus using various treatments, resulting that road can maintain their whole design life

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