Development of Performance Models and Maintenance Standards of Urban Pavements for Network Management

by

Alelí Osorio

A thesis
presented to the University of Waterloo and the Pontificia Universidad Católica de Chile
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Civil Engineering

Waterloo, Ontario, Canada / Santiago, Chile, 2015

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Alelí Osorio Lird

Abstract

Urban pavements in developing countries often provide users with low level of services and result in negative impacts on the population and economy. Two main causes of deferring maintenance actions for urban pavements in developing countries were identified: an institutional organization that limits the optimization of resources assigned to urban pavements because current regulations may not be clear on the responsibilities and faculties of agencies in charge of urban pavement management, and; the lack of effective technical-economic tools that may help agencies in the decision-making process as an updated management system adapted to prevailing urban pavements maintenance requirements.

Although the current state-of-the-art and the-practice of PMSs presents great developments in the last decade for interurban pavements, effective tools developed for urban pavement management are still a missing part of current practices. Compared with the management of interurban roads, the management of urban pavements is a comprehensive task given the complexity of urban networks, the coordination with various services and the variable traffic demands. Given this scenario for urban pavement management, there is a need for better understanding urban pavements performance for network management.

An overall condition index that combines most relevant distresses affecting urban pavements performance is required for network analysis due to several pavement condition indices available were developed for interurban road networks (highways, express corridor, etc.); moreover, several performance models have been developed for particular distresses, and some of them for pavement condition indexes of interurban pavements. Then, their direct application to urban networks (streets, avenues, etc.) is not representative and their adaptability for these conditions requires previous adjustments and calibration.

This research was focused on the network level analysis of urban pavements, towards the development of practical and sustainable technical tools to be further integrated into an Urban Pavement Management System (UPMS). The main objective was to calibrate an Urban Pavement Condition Index (UPCI) and Performance Models, technical components required for an UPMS, based on data collected in urban networks in Chile.

UPCI for asphalt and concrete pavement, based on objective measures of surface distresses and evaluations of an expert panel was successfully calibrated and validated with a confidence level of 95%. Multilineal regressions were performed to obtain the UPCI models.

Three UPCI models were obtained for asphalt pavements with manual and automated data collection. The distresses resulted significance in asphalt pavement condition are fatigue cracking, transverse and reflection cracking, deteriorated patches, rutting, and potholes for manual data collected. IRI replaces potholes in the condition equation for automated data collected. One UPCI model was achieved with successfully validation for concrete pavements with manual data collection. The distresses representative of concrete pavement condition are longitudinal, transversal and oblique cracking, corner breaks, deteriorated patches, faulting, and deteriorate joints and cracks. Deteriorated patches have an important effect in the UPCI value for all UPCIs calibrated, where utility cuts are frequently observed, resulting in low quality patches and high probabilities of premature deterioration. This conclusion supports the primary hypothesis that special condition evaluation guidelines and indicators are required for urban pavements.

Distress evaluation guidelines for asphalt and concrete pavements considering manual and automated surveys were developed and satisfactory validated with a 95% of confidence level through repeatability and reproducibility analysis. This guideline proposes an evaluation methodology for the distresses included in the UPCI. Based on the field evaluation carried out during the research, recommendations about the frequency and sampling for pavement condition evaluation are given for different network hierarchies: primary, every 2 year, the complete network; secondary, every 4 year, the complete network, and; local, every four years samples of homogeneous sections.

Performance models were performed based on probabilistic trends of UPCI observed during field evaluations for asphalt and concrete pavements. Five field evaluation campaigns were developed in three regions of Chile during a three-year analysis period for the calibration and validation of performance models. The climates included were dry, Mediterranean and humid.

The probabilistic trend over time of data collected was analyzed using Markov chains with Monte Carlo simulation that facilitates the analysis of the deterioration trend with only two points of the curve condition over time, allowing the simulation of pavement performance within the timeframe of the research.

Fourteen performance models were calibrated for different combination of three climates, two pavement types and three hierarchy networks, considering a pavement life cycle of 25 years. Twelve of them were successfully validated with a confidence level of 95%. The models of asphalt in humid climate and concrete in dry climate need further analysis for their validation, considering more data collection in these climates.

Hierarchies based on grouped functional classification were used: Primary Network (Express and Troncal streets), Secondary Network (Colectors and Services) and Local Network (Local and passages). Additionally, a comparative analysis was performed between the real equivalent axles demanding the sections and the equivalent axles admitted by their structures, in sections of Mediterranean climate. In other climates, the data was not enough to perform this analysis.

Five models were obtained for asphalt pavement in mediterranean climate: three for the hierarchies and two for the design analysis. The latest two are recommended to use when information about traffic and structure is available. On the contrary, the models developed based on the hierarchy networks are recommended. Two performance models resulted for asphalt pavements in dry and humid climate: Models for humid climate presents higher deterioration rate than model for dry climate. However, both models present a shorter service life than their design.

Likewise asphalts, five models were obtained for concrete pavements in mediterranean climate. Considering the models resulted from the analysis of the design, the deterioration trend does not present big differences within the two conditions analyzed. Therefore, for concrete pavements is recommend the use of the models calibrated based on the hierarchy networks. Two models resulted for concrete pavements in dry and humid climate: Both cases present a long service life; however, on the contrary of what is expected, the dry climate presents a deterioration more accelerated than humid climate. This behavior is probably a consequence of differences in construction standards and maintenance policies, noticed in interviews carried out with agencies of both regions.

Finally, suitable P&M&R standards for urban pavement based on the urban pavement condition index and their performance models were developed for asphalt and concrete pavements. Three different standards are proposed for primary, secondary and local networks.

The practical tools calibrated in this research can be easily implemented and used by local agencies, and simply adaptable over time and to different scenarios. The results of the study were developed with field data collected in Chilean cities; however, the results may be adapted and adopted in other countries for urban pavement management.

Acknowledgements

I would like to begin these acknowledgements expressing my gratitude to my supervisors, Professor Susan Tighe, Professor Alondra Chamorro and Professor Carlos Videla, for their support and guidance in this process. I have learned so much from each of you.

I would like to thank to my examination committee members, Professor Jean Andrey, Professor Jeff Casello, Professor Leo Rothenburg, Professor Tomás Echaveguren, Profesor Claudio Mourgues, and Professor Cristian Vial for taking the time to review my thesis.

The contributions of the professionals from the following agencies to this study is gratefully acknowledge: Fondef Project Team, Chilean Government via Fondef – Conicyt, Ministry of Housing and Urban Development (MINVU), Regional Government of the Metropolitan Region (GORE), Municipality of Santiago, Municipality of Macul, Roads Direction of the Ministry of Public Works and the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, Canada.

I really appreciate the financial support received from the Pontificia Universidad Católica de Chile and the University of Waterloo.

Special thanks to Anibal Godoy for helping me in the field, making easier and funnier the evaluation campaigns.

I am very gratefully of having Cristina Torres as my PhD partner, thanks for your friendship, collaboration and support.

I would like to thank CPATT and PUC teams for their support and friendship, making special recognitions to Laura Bland, Xiomara Sanchez, Marcelo González, Edith Garrido, and William Marquez.

To my friends, who help me in different ways and share with me beautiful moments during the doctoral process, Valeria Ramirez, José Luis Lara, María José Rodriguez, Gonzalo Huerta, Sandra Céspedes, Daniel Olivares, Soledad Alonso, and Claudia Centurión.

Finally, I thank to my family and family in law for their continuous support and love.

Dedication

I dedicate this work to my husband Pancho for his unconditional support and to my children Simón and Jasmín for being my main motivation.

Glossary

µ	Mean
ANOVA	Analysis Of Variance
BPN	British Pendulum Number
CE	Cost-Effectiveness
COB	Sum Of Corner And Oblique Breaks
CONICYT	Comisión Nacional de Investigación Científica y Tecnológica
COTS	Commercial Off-The-Shelf
CPATT	Centre for Pavement and Transportation Technology
CPM	Cumulative Probability Matrices
DP	Deteriorated Patch
ESAL	Equivalent Single-Axle Loads
F	Faulting In Mm, Calculated As The Average Of Faulting Of Each Slab In The Sample Unit
FC	Fatigue Cracking
F_{crit}	Statistical F Value (critic)
FONDEF	Fondo de Fomento al Desarrollo Científico y Tecnológico
F-tests	Statistical F Distribution
FWD	Falling Weight Deflectometer
GIS	Geographic Information System
GORE	Regional Government of the Metropolitan Region
GPS	Global Positioning System
GTZ	German Agency for Technical Cooperation
H0	Null Hypothesis
H1	Alternative Hypothesis
HS	Homogeneus Sections
IRI	International Roughness Index
JD	Joint Damage In Percentage Of The Total Meters Of Joints In The Sample Unit
LC	Longitudinal Cracking
MANVU	PMS Tool
MANVUSIMP	Metodología Simplificada para Evaluar Proyectos de Mantenimiento Vial Urbano
MINVU	Ministry of Housing and Urban Development
MOP	Ministry of Public Works
P	Potholes
P&M&R	Preservation, Maintenance and Rehabilitation
PM	Pavement Management

PMA	Pavement Management Application
PMS	Pavement Management System
PQI	Pavement Quality Index
PSD	Proprietary Systems Developed
PTM	Probability Transition Matrices
R	Rutting In Mm, Calculated As The Average Of Rutting Of Segments In The Sample Unit
RIII	Roughometer III
SAMPU	PMS Software
SDI	Surface Distress Index
SEREMI	Ministerial Regional Secretariat
SERVIU	Regional Housing and Urban Services
SPF	Socio-Political Criteria
SU	Sample Unit
TC	Transversal Cracking
t_{crit}	Statistical t Value (critic)
TRC	Sum Of Transversal And Reflection Cracking
UPCI	Urban Pavement Condition Index
UPMS	Urban Pavements Management System

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Chapter 1

Introduction

1.1 Background

1.1.1 Urban Pavement Condition

Urban pavements play a vital role in cities development; however, bad conditions of streets are frequent in many cities, especially in developing countries. Figure 1-1 shows different distresses found in streets of Santiago, Chile.

Figure 1-1. Distresses in streets of Santiago, Chile

Pavements in bad conditions cause negative impacts in the population and cities, such as decreasing quality of life, road safety, increasing user costs and pollution (PUC 2010).

Two main reasons of bad condition of urban pavements in developing countries were identified: current regulations are not clear on the responsibilities and faculties of agencies in charge of urban pavement management, and; the lack of an effective and sustainable tool that helps agencies in the decision-making process for urban pavements maintenance requirements (PUC 2010).

In order to define a tool for decision-making of urban pavements maintenance requirements, first the pavement performance process it must be analyzed.

1.1.2 Pavements Performance and Maintenance

Pavements deteriorate over time due to the effect of stresses caused by traffic and the environment. How pavements respond to these stresses will depend on: the pavement structure, such as pavement type, layers thickness and subgrade properties; construction characteristics, including construction technologies, quality and; and pavement maintenance, such as treatments applied, timing, and methods. However, the way their conditions evolve over time will depend on the combined effect of these factors as illustrated in Figure 1-2 (TAC 2013; Tighe S. et al. 2007)(Chamorro and Tighe 2009; TAC 2013).

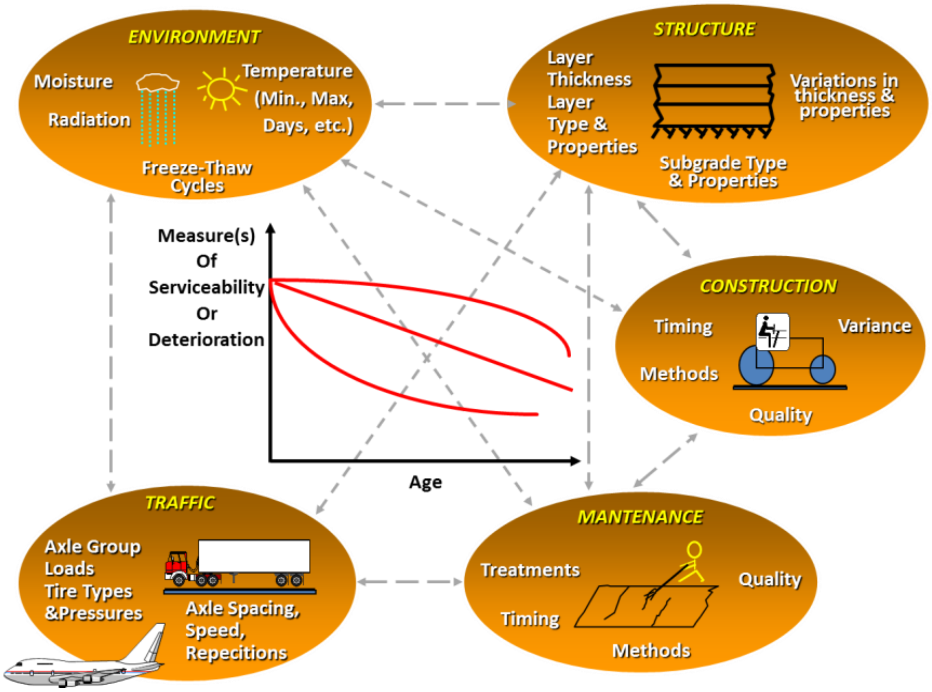


Figure 1-2. Factors involved in pavement performance (TAC 2013; Tighe S. et al. 2007)

Pavement performance at a certain time of the service life can be characterized and assessed in terms of particular distresses or a combined index that represents the pavement overall condition. The factors involved in the determination of the pavement condition are the pavement type and the distresses observed. In both cases, the performance indicator reflects the pavement condition at a specific age of the pavement service life.

It is important not only to understand the current condition of pavements, but also to understand how their condition will change over time. The pavement condition deterioration over time is represented by performance models. These models correspond to mathematical expressions for predicting the pavement condition evolution throughout its lifetime (de Solminihac 2001).

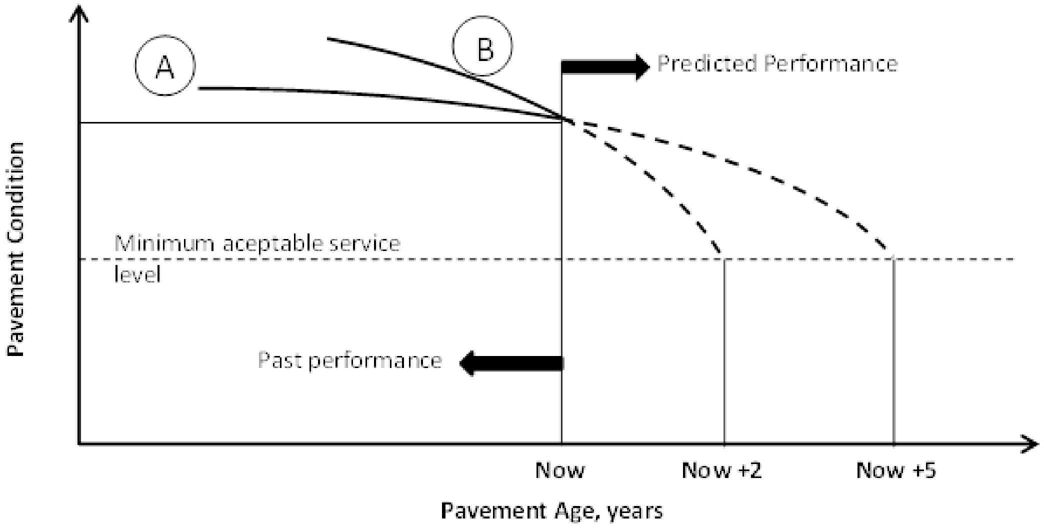


Figure 1-3. Deterioration over time of two different pavements (Adapted from (NGSMI 2002; TAC 2013))

Figure 1-3 shows how two pavements of different characteristics can have the same condition at a given time of their life cycle, but their performance models are completely dissimilar. Pavement B has higher rate of deterioration than pavement A. Thus, pavement B will reach the minimum acceptable service level sooner (TAC 2013). Therefore, the needs of maintenance would be also different.

For this reason, the effectiveness of maintenance treatments over time relies on making the decision based on the current pavement condition and its performance model. In other words, is to performed life cycle analysis of pavements for maintenance definition.

The typical cycle of pavement deterioration comprises three stages (Schliesser and Bull 1992), as is showed in Figure 1-4. These stages are related to different types of maintenance:

- Slow Phase (Phase A on Figure 1-4): During several years, the pavement experiences slow deterioration process, particularly in the surface, and also, though to a lesser degree, the rest of its structure. The deterioration rate depends on the quality of the initial construction. To stop this process of deterioration is necessary to apply, with some frequency, various maintenance treatments, mostly on pavement surface and drainage works. The group of these maintenance activities is defined as Preservation. Furthermore, it should perform routine maintenance.
- Accelerated Phase (Phase B on Figure 1-4): After several years of use, the pavement enters a stage of accelerated deterioration. At the beginning of this phase, the basic structure of the pavement is still intact, the surface distresses are minor, and common user has the impression that it still remains in good condition; however, it is not. Going further in phase B, more damage to the surface it is observed and the basic structure begins to deteriorate, which is not visible. These distresses begin being punctual, and slowly spread until eventually affect most of the pavement surface. This phase is relatively short. Once the surface damage is widespread, destruction is accelerated. At the start of this phase is usually sufficient to reinforce the pavement surface, so maintenance is relatively low cost.

Once a suitable reinforcement is applied, the pavement again is suitable for function and can withstand the traffic for a lot of years more. This type of activities is defined as Functional Maintenance or simply Maintenance.

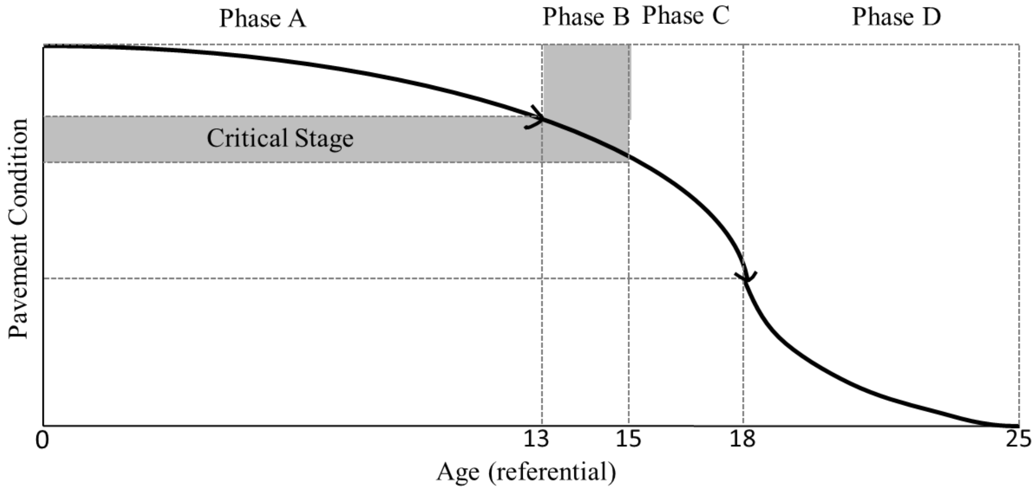


Figure 1-4 Pavement Life Cycle (Adapted from (Schliesser and Bull 1992))

- Break Phase (Phase C on Figure 1-4): After the accelerate phase, the optimal intervention time pass and when more intervention is delayed, greater the damage and also higher repairs will be needed to the basic structure of the pavement. The damage occurred in the basic structure of the road must be repaired, which means demolishing and lift the damaged parts, replacing components for new ones and subsequently, all the reinforcement on the pavement surface is placed. This group of activities is frequently named Structural Maintenance or Rehabilitation, when it refers to the combination of partial repairs on the basic structure of the road to strengthening its surface.
- Decomposition Phase (Phase D on Figure 1-4): When not interventions are applied in any time of previous phases, the pavement reaches the point of breakdown, and failure widespread both the pavement surface and basic structure. Decomposition of the road is the last stage of its existence and can last several years. At this phase the only solution is the reconstruction of the pavement.

Based on the deterioration stages is essential to consider maintenance activities for each stage to optimize resources and extend the service life of pavement with a good condition. Thus, activities for preservation, maintenance and rehabilitation (P&M&R) need to be defined for application throughout pavement service life.

1.1.3 Urban Pavements Management

Pavement Management (PM) is a discipline that helps to improve the efficiency of the decision-making process and provides feedback regarding the effectiveness of decisions related to P&M&R

activities and ensures the consistency of decisions made at different levels within the same organization (AASHTO 1993; TAC 2013).

A Pavement Management System (PMS) is a tool used in PM to make informed decisions about the sustainable impacts of the P&M&R activities on a pavement or network. Overall, Pavement Management is looking for optimal decisions for pavement P&M&R treatments and the PMS is a combination of tools to achieve this goal. A PMS should consider the life cycle assessment of pavement performance over time to compare the effectiveness of various types of treatments. For this, effective evaluations of road conditions and reliable condition performance models are necessary (Chamorro and Tighe 2011).

The PM have been categorized into three main levels (Haas et al. 1994; de Solminihac 2001; TAC 2013):

- Strategic Level: Defines the overall goals and incorporates the institution policies and budget available for pavement maintenance and rehabilitation.
- Network Level: Has the primary purpose of developing priority programs and schedule of work, within overall budget constraints.
- Project Level: Has the objective to decide the appropriate time in the schedule and represents the actual physical implementation of network decisions. Project Level addresses the design, construction, and maintenance associated with a particular section of pavement.

Network level is the appropriate management level to apply when the maintenance prioritization of streets within a city is required.

Although the current state-of-the-art and the-practice of PMSs present various developments over the last decade, specific limitations for network management of urban pavements are still a missing part of current practices.

In order to understand the comprehensive management inherent to urban pavement networks, it is important to first note the differences of pavement management within urban and interurban networks, such as the following (PUC 2010; TAC 2013):

- Institutional Aspects: Generally the institutions in charge of urban pavements are smaller than the interurban pavement, which is associated with fewer technical resources and less funding available. This situation makes the management of urban pavements more difficult and demands more planning of activities.
- Inventory Data: One of the main differences between urban and interurban pavements is the cross-section of an urban street versus an interurban highway. An urban PMS requires more data regarding the elements surrounding the pavement, such as sidewalks, curbs, medians, gutters, signs, fire hydrants, hydropoles, manholes and catch basins. The historical data constitute an additional major difference between urban and interurban pavements because a large number of urban pavements were constructed by layer over a long period of time.
- Rehabilitation Alternatives: The selection of the rehabilitation alternatives is limited by the available curb height in urban areas. The curb height dictates the thickness for resurfacing a road. Often the road must be milled prior to overlaying, while in interurban areas, the road can often just be overlaid.

- Influence of Distresses on Serviceability: The distresses on urban pavement have a different impact on the serviceability. In some studies, roughness was found to be the most important factor in deriving the overall combined index of highways, and the surface condition was found to be the most important factor for urban pavements, mainly due to the impact of the various distresses over riding for different service speeds.
- Sectioning Criteria: An urban PMS requires more sections than an interurban PMS. In many cases, the streets have a different traffic flow or different materials in each direction, so the road has to be considered as different sections.
- Data Collection Methodologies: Urban and interurban PMSs can have the same methodology for data collection, but there is equipment that needs a higher minimum speed to operate, which can be complicated on urban streets. Additionally, the frequency and sample size can vary for urban pavements.
- Pavement Structures: On the one hand, the urban pavement may have a stronger structure due to the higher traffic volumes and slower operating speeds. On the other hand, in some cities, the pavements have a composite structure consisting of many types of different pavement layers. For these reasons, the development of the performance models can be more complex for urban PMSs.
- Urban Pavement Deterioration: This factor is more complex for urban streets and involves more than the interactions between traffic, climate, materials and time. There are also singularities such as manholes and catch basins that influence the pavement deterioration and pavement interventions for utility cuts that affect pavement deterioration. Utility cuts for installation or maintenance of urban services in the underground are a complex duty to deal with for the urban performance models.

Agencies commonly use deterioration indices for network level decision making, which may combine different types of surface distresses, serviceability and structural indicators (Wolters, A. et al. 2011). Examples of these indices are: Pavement Condition Index (PCI) (Reza, F. et al. 2006), Distress Manifestation Index for Network Level (DMI) (Chamorro et al. 2009b), Índice de Condición de Caminos Pavimentados (ICP) (MOP 2006), and Índice de Serviciabilidad (P) (MINVU 1999). Almost all these indices differ in the types of deterioration and criteria considered to quantify severity and density of distresses. However, these indices were developed for interurban road networks (highways, express corridor, etc.); therefore, their direct application to urban networks (streets, avenues, etc.), is not representative and requires calibration and validation. The Serviceability Index (P) (MINVU 1999) was defined for urban pavements but consider as an important characteristic the roughness rather than other distresses; then, .the analysis and calibration considering other distresses present in urban environment is needed for its application.

Once a representative index is defined, its evolution over time should be analyzed through condition performance models. Several performance models are available in the state-of-the-art and the-practice (Arambula E. et al. 2011; Chamorro and Tighe 2011; Chan P. et al. 1997; Kargag-Ostadi N. et al. 2010; Mubaraki M. 2010; NCHRP 2010; Odartey L. et al. 2012; Rahim A. et al. 2013; Tack J. and Chou Y. 2001); however, these were developed for combined indices of interurban pavements (highways, express corridor, etc.) or their main focus has been the progression of specific distresses overtime for project level analysis rather than the progression of the overall condition of pavements for network level management. Therefore, their direct application to urban pavement networks (streets, avenues, etc.) is limited, requires adaptation and further calibration and validation (Osorio et al. 2014). In addition, the tool Manusimp and Sampu (MINVU 1999) that were developed for urban pavement management in Chile, consider in their analysis performance models for asphalt and concrete developed for other conditions without a previous adaptation.

1.2 Problem Definition and Research Approach

The discussion presented in the background left important premises about limitations on the state-of-the-art and the-practice on Urban Pavement Management:

- Based on pavement deterioration stages, it is essential to consider P&M&R activities that optimize resources and extend the service life of pavement with a good level of service. Effectiveness of maintenance treatments over time relies on making the decision based on life cycle analysis of pavements for maintenance definition; thus, the current pavement condition and its performance models need to be considered.
- An overall condition index that combines most relevant distresses affecting urban pavements performance is required for network analysis due to several pavement condition indices available were developed for interurban road networks (highways, express corridor, etc.); then, their direct application to urban networks (streets, avenues, etc.), is not representative and requires calibration and validation. Moreover, considering developing countries, economic resources for semi-automated or automated evaluations are not always available; therefore, an evaluation methodology considering manual or automated field evaluation is needed.
- Several performance models found in the literature have been developed for particular distresses, and some of them for pavement condition indexes of interurban pavements. Therefore, their direct application for urban pavement conditions is not representative and their adaptability for these conditions requires previous adjustments and calibration.
- Available P&M&R standards include some maintenance activities not appropriate for urban conditions as well as are their applications thresholds are define based on particular distresses or pavement condition indexes for interurban pavements, and their performance models. Consequently, they are not adoptable for direct use in urban pavements.

Given the important differences observed between urban and interurban networks in terms of pavement performance, traffic demands and network characteristics, summed to the fact that most of the state-of-the-art and the-practice have focused on interurban pavement network management, the development of management tools for urban streets are needed.

Furthermore, there is a need for better understanding urban pavements performance for network management. Therefore, this research is focused on the network level analysis of urban pavements due to its lower level of development and the need to generate global knowledge, directing toward the development of practical technical tools to be integrated into an Urban Pavement Management System.

The research approach considers a detailed analysis of the current state-of-the-practice of urban pavement management. Based on this analysis, an Urban Pavement Management Framework is proposed considering criteria for sustainable management. This is followed by the development and validation of: a methodology for urban pavement condition evaluation considering an overall condition index; the urban pavement performance models adaptable for different climates, structures and traffic, and; the recommendation of suitable P&M&R standards for urban pavements based on the overall pavement condition and their performance models.

This research was part of a three year project developed in Chile "Research and Development of Solutions for Urban Pavement Management in Chile". Other parts of this project addressed the limitations that are not included in this research, such as institutional regulations adjustments and the development of the other components of PMS for urban pavements.

1.3 Hypotheses

The hypotheses of the research are defined as follows:

1. The Urban Pavement Condition Index is correlated to objective measures of distresses obtained from field, through manual and automated evaluations.
2. The probabilistic trend of Urban Pavement Condition Index over time is modelled from field measures considering different climates, structures, traffic, and pavement types.

1.4 Objectives

1.4.1 Overall Objective

Calibrate an Urban Pavement Condition Index (UPCI) and Performance Models, technical components required for an Urban Pavement Management System, based on data collected in urban networks in Chile.

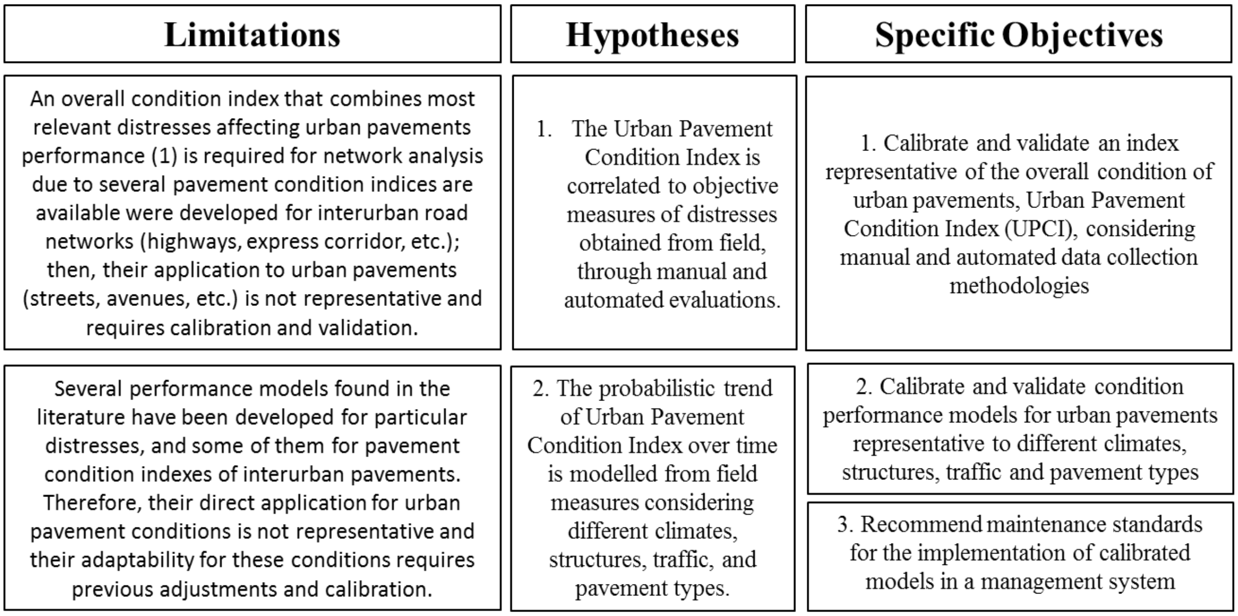
The aim will be to develop practical tools that can easily be implemented and used by local agencies and are adaptable over time and to different scenarios.

1.4.2 Specific Objectives

To achieve the main objective of the research, the following specific objectives must be fulfilled:

1. Calibrate and validate an index representative of the overall condition of urban pavements, Urban Pavement Condition Index (UPCI), considering manual and automated data collection methodologies
2. Calibrate and validate condition performance models for urban pavements representative to different climates, structures, traffic and pavement types
3. Recommend maintenance standards for the implementation of calibrated models in a management system

Figure 1-5 shows the interaction between the limitations found in the state-of-the-art and the-practice for urban pavement management with the hypotheses and specific objectives raised in this research.



Limitations	Hypotheses	Specific Objectives
An overall condition index that combines most relevant distresses affecting urban pavements performance (1) is required for network analysis due to several pavement condition indices are available were developed for interurban road networks (highways, express corridor, etc.); then, their application to urban pavements (streets, avenues, etc.) is not representative and requires calibration and validation.	1. The Urban Pavement Condition Index is correlated to objective measures of distresses obtained from field, through manual and automated evaluations.	1. Calibrate and validate an index representative of the overall condition of urban pavements, Urban Pavement Condition Index (UPCI), considering manual and automated data collection methodologies
Several performance models found in the literature have been developed for particular distresses, and some of them for pavement condition indexes of interurban pavements. Therefore, their direct application for urban pavement conditions is not representative and their adaptability for these conditions requires previous adjustments and calibration.	2. The probabilistic trend of Urban Pavement Condition Index over time is modelled from field measures considering different climates, structures, traffic, and pavement types.	2. Calibrate and validate condition performance models for urban pavements representative to different climates, structures, traffic and pavement types 3. Recommend maintenance standards for the implementation of calibrated models in a management system

Figure 1-5. Limitations, Hypotheses and Objectives Interaction

1.5 Methodology

The proposed research methodology is presented in Figure 1-6. The research methodology considers the four main stages and divided in several activities, as described in the following paragraphs:

Activities developed throughout the research

- State-of-the-art and the-practice Review: The research began with a review of the state-of-the-art in pavement management systems in general and specifically for urban pavements. The goal was to understand the international state of the practice and resulted in interviewing local agencies from various countries. For the state of practice in Chile, interviews and surveys were developed. This stage have extended throughout all of the research, carrying out a more specific review of each subject at the beginning of each stage of the research, of topics such as types of pavement distresses and their preservation and maintenance activities, methodologies of pavement technical evaluation, existing pavement performance models and techniques available for modeling.
- Field Evaluations: This phase included five evaluation campaigns to locate the data defined as a requirement for each stage in the experimental design. Manual and automated evaluations were performed, as well as evaluations based on professional experience. The methodology followed in this stage was defined in the experimental designs.

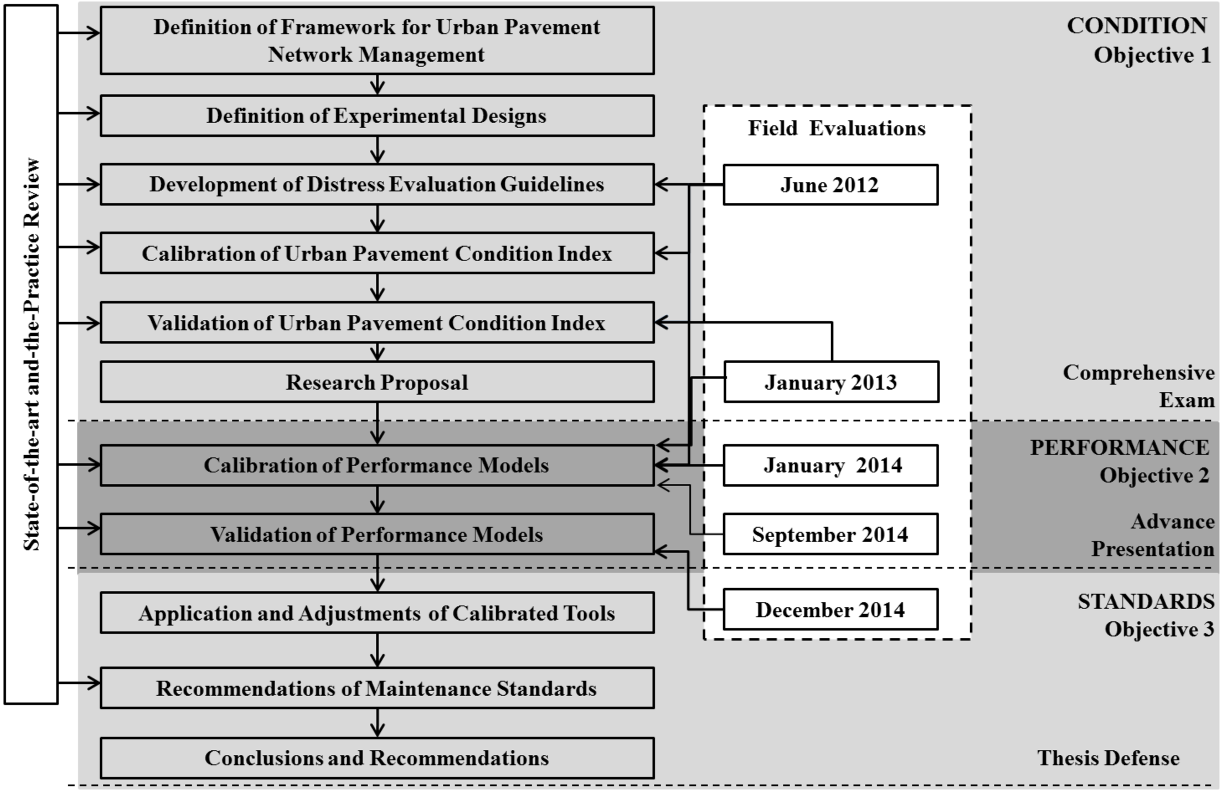


Figure 1-6. Research Methodology

Stage 1

- Development of a Management Framework for Urban Pavement Networks: Based on the state-of-the-art and the-practice of UPMSs, at this stage, a theoretical framework management was developed as a basis for the development of the Urban Pavement Management System.
- Definition of Experimental Designs: This stage included the preparation of the experimental design required to develop each of next three stages. Each experimental design have included the variables, dependent and independent, the factorial design for the data collection and the methodology to be followed for the data collection and analysis.
- Development of Distress Evaluation Guidelines: This methodology included the development and selection of the distress evaluation methodology for manual and automated data collection for urban pavements, based on available literature and field observations.
- Calibration of Urban Pavement Condition Index (UPCI): The calibration of Urban Pavement Condition Index to represent the overall condition of urban pavements with statistical analysis of data collected in manual and automated field evaluations.
- Validation of Urban Pavement Condition Index: The validation of the UPCI was performed with statistical analysis of data saved for this purpose.

- Research Proposal: The research plan proposal was developed based on the activities carried out in the previous activities. Recommendations and feedback obtained in technical meetings with the supervisors of this thesis, and from the Comprehensive Exam Committee were incorporated into the research proposal.

Stage 2

- Calibration of Performance Models: This stage included the creation of hierarchies of urban pavement in Chilean networks based on the functional classification of the streets, type of pavement, structure and traffic, based on data collected; and the calibration of performance models for urban pavements from probabilistic analysis of pavement conditions collected in the field for different climates and hierarchies
- Validation of Performance Models: The validation of the performance models was performed with statistical analysis of data saved for this purpose.

Stage 3

- Application and Adjustments of the Technical Components Developed: Once the tools were developed, applications were performed to evaluate the results, and adjustments were done in the components.
- Recommendations of Maintenance Standards for Urban Pavement Maintenance: Preservation, maintenance and rehabilitation activities were selected for different hierarchies with thresholds depending on different pavements types, UPCI values and their impacts on the pavement condition.
- Conclusions and Recommendations: Final conclusions and recommendations were made about the research findings, the implementation and use of the developed technical tools.

1.6 Scope of the Research

This is a comprehensive research initiative that intends to evaluate details and characteristics of the urban pavement performance that have not been clearly evaluated in the past.

To calibrate and validate the technical tools proposed, the levels of independent variables to be included were limited to the following criteria for the development of performance models and the definition of P&M&R standards: 1) Climate Types: Mediterranean in the city of Santiago with flat terrain, Dry in the city of Antofagasta with undulated terrain, and Humid in the city of Puerto Montt with undulated terrain; and 2) Pavement Types: asphalt and concrete. Interlocking pavements were also analyzed at the beginning of the research but only for the development of the methodology of Condition Evaluation.

1.7 Thesis Organization

The thesis document is organized in the following chapters:

1. Introduction: In this introductory chapter the background about pavement deterioration and maintenance, and urban pavement management were first presented. Then, the problem definition, research hypotheses, objectives and methodology were defined accordingly.

2. Literature Review: This chapter presents the state-of-the-art and the-practice review. This includes types of pavement management systems, methodologies of pavement condition evaluation, pavement performance models and maintenance standards characteristics. Finally, the limitations and opportunities of improvement are presented.
3. Urban Pavement Management Framework: A framework for urban pavement management is proposed including sustainable criteria for network analysis. This framework comprises four components: input data, methodologies, processes and outputs. A detailed description of each component and the interaction between them is presented.
4. Experimental Designs and Data Collection: This chapter presents the experimental design for the calibration and validation of the technical tools. A total of three experiments were defined, one for each of the following activities: Calibration and Validation of Evaluation guidelines, Calibration and Validation of Urban Pavement Condition Index, and Recommendation of Maintenance Standards.
5. Data Collection and Processing: In this Chapter are presented the methodologies followed to collect the data in the field and then process them. In addition, a summary of the data collected is presented.
6. Calibration and Validation of Urban Pavement Condition Index: First, the methodology followed for the development and validation is presented. Then, the development and validation of evaluation guidelines is discussed. Finally, the development and validation of UPCI is presented.
7. Performance Models: This chapter presents in first place the methodology for development and validation of performance models. Then, the development, validation, analysis and recommendations of performance models is discussed.
8. Maintenance Standards: The methodology for the development and validation of maintenance standards is first presented. Then, the definition of treatments considered for the standards definition is showed with theirs threshold of application, the effects in the UPCI and the maximum UPCI reachable.
9. Conclusions and Recommendations: Conclusions of the research, recommendations for implementation and use of the developed tools, thesis contributions, and future research and developments are presented in this chapter.

Chapter 2

Literature Review

2.1 Pavement Management Systems

A PMS should integrate and coordinate all aspects considered in the management process of pavement assets. In particular, the comprehensive PMS should account for a dynamic process that incorporates feedback regarding the various attributes, criteria, and constraints involved in the optimization of maintenance programming and decision making (TAC 2013).

However, it is important to emphasize that the PMS itself does not make the decisions. A PMS converts raw data into usable information, but the decisions are made by the people using the information provided by the PMS.

PMSs should be developed according to the technical and socio-economic needs of each type of pavements and level of analysis.

A PMS must contain the following essential characteristics (TAC 2013):

- Adaptability: To update models easily as new information becomes available.
- Practical: To consider different alternative strategies.
- Efficient: To identify the optimum alternative or strategy.
- Quantitative Based Decision-Making Support: To be capable of making decisions based on rational procedures with quantified attributes, criteria and constraints.
- Good Feedback Information: To provide feedback information regarding the consequences of decisions.

Initial PMS development involved practicing “worst first” strategies. There are still agencies that have not implemented PMS or are using a simple PMS with the prioritization analysis to define the list of candidate pavements based only on a ranking process. That approach results in a reactive strategy.

Current PMSs involve a proactive strategy. The pavement managers research treatments and technologies and use a prioritization analysis inside the PMS such as pavement preservation, network optimization or priority assessment models. Many studies show that these methodologies tend to be more cost-effective in a long-term analysis than the reactive strategy (Tan and Cheng 2012).

Furthermore, the criteria traditionally considered in evaluating maintenance alternatives have been the technical and economic. The evaluation of infrastructure investments through economic analysis allows administrations better manage their resources, maximizing social benefits and allowing greater transparency and accountability (FHWA 2003a; Torres-Machi C. 2015). However, if we consider the definition of sustainable development, defined as "Meets the needs of present without compromising the ability of future generations to meet their own needs" (Torres-Machi C. 2015; WCED 1987), it seems that considering only technical and economic criteria is insufficient for sustainable pavement management. In fact, sustainable management requires integrated consideration of technical, economic, environmental and social criteria (Torres-Machi C. 2015; UN 2005).

2.1.1 PMS Components

A PMS should be an engineering-based simulation of the decision-making process carried out by public agencies and private companies involved in pavement management, which integrates the progression of activities involved in efficiently solving the management problem. It should be composed of the following components (TAC 2013):

- Information: Provides the basic foundation for the analysis. The information must include Inventory (including pavement structure and geometry); environment; road usage (traffic volume and loading, usually measured in equivalent single-axle loads (ESALs); pavement condition (ride quality, surface distresses, friction, and/or structural capacity); pavement construction, maintenance, and rehabilitation history; existing projects for the overall network; and available resources such as materials, etc.
- Technical Analysis: Should include the definition of what attributes of the pavement should be measured, with methods and equipment needed to do the field evaluation. The measurements can be structural capacity, ride quality, surface condition, skid resistance, etc. The method has to define the sample and the degree of accuracy and frequency appropriate to the class of road involved, agency resources, etc. (Tighe S. et al. 2008).
- Performance Models: Pavement performance prediction models are used to predict future pavement conditions of the pavement network as part of the agency's pavement management activities. The models must reflect the best possible representation of the pavement deterioration at the time. Predicting pavement performance is an essential activity of a pavement management system for optimizing the combination of projects, M&R treatments, and timing of application to achieve agency goals; predicting the length of time until a lower limit of acceptable pavement condition is reached; evaluating the long-term impacts of various program scenarios; providing a feedback loop to the pavement design process; and estimating pavement life-cycle costs (Assaf. G.J. et al. 2006; Hein, D. and Watt, D. 2005; Rajagopal, A. 2006).
- Maintenance Strategies: Consist of the determination of standards and thresholds for maximum roughness and surface distress and minimum structural adequacy and surface friction, alternatives of maintenance and rehabilitation treatments and the combination of those, and the estimation of approximate unit cost for each of them.
- Economic Analysis: Includes the selection of program analysis period, discount rate, etc., identification of what economic analysis should be used for the specific PMS, and economic analysis of each alternative in terms of calculating life-cycle costs and benefits or cost-effectiveness.
- Prioritization and Optimization: Once a list of pavement segments requiring repair has been identified and the proper feasible repair has been selected considering the associated costs and benefits, the work needs to be prioritized based on criteria established and budget constraints. The pavement management software should contain priority models to prioritize the different pavement projects within each analysis year. These models may range from simple ranking routines to complex optimization models.

The characteristics of each component of the PMS should be established based on the needs of the agencies. The goals and specific objectives to achieve by the PMS must be clearly defined.

2.1.2 Urban Pavement Management Systems

The existing PMSs can be classified as (Mizusawa 2009):

- “Commercial Off-The-Shelf” (COTS) systems: COTS systems are defined as an application or system software that is marketed widely to transportation agencies as a prepackaged product under an established commercial licensing or leasing agreement.
- Proprietary Systems Developed (PSD): PSDs are systems that were built especially to meet the institution’s specific needs. PSDs can either be developed by an external consultant or developed in house.

Table 2-1 summarized the potential advantages and disadvantages of using one of the COTS systems over proprietary systems developed. This summary table was carried out based on the information provided by McPherson (McPherson and Bennett 2005).

Table 2-1. COTS. Advantages and Disadvantages

Advantages	**Cost:** COTS systems are usually much cheaper to buy than to develop.
	Independence: Many consultant suppliers may be able to offer implementation support.
	Time frame: The COTS systems can be implemented more quickly.
	Experience: The systems have usually been implemented in a number of other client organizations for a number of years and have therefore been subjected to rigorous user testing as well as in-house testing conducted by suppliers.
	Functionality: The systems often provide more useful functionality than a client originally considered.
	Ongoing Development: The systems are usually continually upgraded by a supplier to respond to other client requests for enhancements.
	Exchange of Ideas: The information of the systems is shared with users through user conferences held by suppliers.
Disadvantages:	**Requirements:** The system functionality may not be exactly what is required by a client, and some workarounds may therefore be needed.
	Institutionalization: The systems may not have institutional acceptance because they do not reflect the current business processes of a client.
	Customization: The systems with new ideas need a longer time to be implemented because those suppliers have a responsibility to other clients as well.
	Maintenance Cost: The support and maintenance agreements for the systems are usually on the order of 12-20% per annum of their original costs.
	Upgrades: The upgrade of the systems is controlled by the developers, and clients are often compelled to follow the developer’s schedule to ensure future system maintenance.

2.1.2.1 COTS PMS Available for Urban Pavements

A variety of COTS systems are available in the market with different characteristics of analysis level, segmentation, possible adaptability, etc. All of these COTS systems can be used for urban pavement management, but an important criterion for selecting a COTS system is the flexibility to customize the components because many of them were developed for interurban pavement networks.

Table 2-2 presents a summary with the main characteristics of the COTS PMSs available in the market based on the literature review. This summary was performed with information obtained in the state-of-the-art review and several interviews performed in order to capture the state-of-the-practice of different softwares (AgileAssets Inc. 2010; Cartegraph 2013; Colorado State University 2013; Deighton 2012; JG3 2012 p. 3; Mizusawa 2009; MTC 2009; SMEC 2012; Stantec 2009).

Table 2-2. COTS Summary Table

COTS PMS	Origin	Analysis Level	Dinamic Segmentation	Condition Index	Economic Analysis	Integration with GIS	Adaptability of all components	Other Assets Inventory	Number of Cities using	Adaptability to local terminologies /leanguage
Micropaver	USA	Network / Project	Yes	PCI	Cost Effectiveness	Yes	No	No	600	No
Pavement View	USA	Network / Project	Yes	OCI	Capital Improvement Plans	Yes	Yes	Yes	unknown	Yes
SMEC	Australia	Network / Project	Yes	PCI	Cost benefit analysis/ Heuristic Decision Rules	Yes	No	Yes	60	Yes
HPMA	Canada	Network / Project	Yes	PQI	Cost benefit analysis/ Heuristic Decision Rules	Yes	Yes	Yes	2	Yes
Road Matrix	Canada	Network / Project	No	PQI	Cost Effectiveness	Yes	Yes	Yes	79	Yes
StreetSaver	USA	Network	No	PCI	Cost Effectiveness	Yes	No	No	300	No
dTIMS CT	Canada	Network / Project	Yes	PQI	Benefit-cost analysis	Yes	Yes	Yes	> 40	Yes
AggileAssets	USA	Network / Project		PCI	Cost Effectiveness	Yes	Yes	No	unknown	Yes

2.1.2.2 Proprietary Systems Developed: Case Study Examples

Based on the literature review, there are PMSs especially developed for agencies in charge of urban pavement management to manage their pavements. The PMSs described in the following paragraphs are presented due to they are frequently mentioned in the literature review. The common characteristic of all of these PMSs is that the components were developed specifically for their local conditions. However, none of them use performance models of combined indicators for assigning maintenance activities. Some assign maintenance activities based only on the current condition and, others use performance models of particular distresses separately and then, determine the combined condition with distresses data.

- Alberta’s Municipal Pavement Management System, Canada (Jestin, R. 2011)

Alberta's Municipal Pavement Management System (MPMS) provides the information and tools for network programming of street maintenance and rehabilitation and project level rehabilitation design. The scope of the MPMS includes the following functional requirements: Interactive sectional data entry and update; Performance data/index conversion, Data base reporting (sectional and network aggregates), Street maintenance information and needs analysis, Maintenance strategy and financial analysis, Network rehabilitation needs and alternatives analysis, Network rehabilitation priority programming analysis, Project level structural requirements analysis, and Project level rehabilitation alternatives analysis.

Many cities in Canada have adopted this PMS during the last decade and continue applying an updated version with an integrated GIS. The updated version for many cities was adjusted to the Road Matrix software.

The cities of Edmonton and Calgary are using the updated version in the HDMA software, which was customized for them. Both cities managers selected this COTS PMS due to the dynamic segmentation and the Heuristic Decision Rules for prioritization.

- StreetWise, Washington State – USA (Broten 1996; Sachs 1996)

The Washington State Department of Transportation (WSDOT) PMS was adapted for utilization by local agencies in the late 1980s. Larger cities and counties had adopted this system for their urban streets without difficulty. However, smaller cities usually could not afford it due to the complexity of the system. In response to that need, WSDOT has developed a manual that is based on the computerized systems in the state, but it can be filled out with pencil and paper. This simplified system is still being used in smaller cities and allows cities in WS to customize the system for their specific needs. The PMS has a very complete manual for implementation and application in different conditions.

After implementing the pavement management software, the models can be adjusted within the program. In addition, a few agencies use actual data collected over time and stored in the pavement management database to improve the models used in the software. This feedback process enables agencies to continually improve the PMS as they learn more about their system and streets.

Evaluation methods include how to evaluate, what conditions to evaluate, and how often to evaluate. For example, it is common for these agencies to inspect arterials every other year and other streets (such as local access and residential) every three years. It is common for an agency to inspect annually when it is just starting the pavement management process, so that the agency can rapidly establish a historical database of conditions. Once three inspection cycles have been completed, the frequency of inspections is decreased. Most cities interviewed stated that a two-year inspection cycle was desirable.

One peculiarity of this PMS is that the managers of the cities involve the public in the pavement management process whenever possible. An example of this involvement is the city of Seattle, where the neighborhood associations provide their input on the prioritization of road work.

- City of Seal Beach, California – USA (Nichols Consulting Engineers, CHTD 2010)

The City of Seal Beach has used a pavement management program to manage its street network since 2004. First, they customized the StreetSaver program, but in 2010, the City converted to the MicroPAVER software to be compliant with the requirements of the Orange County Transportation Authority (OCTA).

- Bowling Green, Utah – USA (Lashlee et al. 2004)

The City of Bowling Green started to develop a pavement management system in 1998 to help employ proper maintenance to retain a quality transportation network. After the first survey, they decided to adopt the COTS PMS Pavement Management Application (PMA) that is the former version of the HPMA.

Since that time, existing data and specialized survey data from Stantec, Inc., have consistently made updates. Currently, Stantec conducts a resurvey of half of the network each year for surface and ride conditions in three-year intervals. On the third year, only deflection or structural-type testing is performed. This cycle helps to ensure the data that are used are relatively current and appropriate decisions are made. Given all update methods, a large amount of data is stored and accessed.

The PMA data are then linked with the City's geographic information system (GIS) for mapping and visualization. The analysis of the City's Pavement Management System includes four main indices for pavement condition. These indices are Surface Distress Index (SDI), Ride Comfort Index (RCI), Structural Adequacy Index (SAI), and a composite of the previous indices, the Pavement Quality Index (PQI).

- G-PMS, Salt Lake, Utah – USA (Cottrell W. et al. 2006)

The Wasatch Front Regional Council (WFRC) in Utah was challenged to cooperate with states and local agencies in developing regional pavement management systems for highway and urban streets. The development was particularly difficult because some of the local agencies already had well-established PMSs that were sufficient for their needs.

Eight PMSs were being used in the Salt Lake City–Ogden area by those communities having a formal PMS. This diversity caused concern amongst the local pavement management specialists regarding PMS alterations to serve a new regional PMS. A few agencies were using different COTS PMSs, and the others had an informal PMS founded on the judgment and experience of local engineers.

However, 14 localities had no PMS. The disparity between local pavement management activities indicated that the responsibility for pavement data collection and conditions and performance analyses should be allocated to the state to eliminate the potential inconsistencies associated with having the localities report pavement conditions. This approach may be applicable in similar urban regions where there is extreme variation in the degree of local pavement management.

An outline for incorporating the regional PMSs for local agencies was developed. The emphasis will be on using the PMS to make programming decisions. An automated pavement condition data collection system for urban streets in the region will be established. The PMS to use will be the dTIMS program, which will be customized to local needs. The WFRC must digest this information and prioritize the suggested rehabilitation projects.

- SAMPU (Minvu)

The first methodology for urban pavement management in Chile was developed 20 year ago under the name of MANVU (MINVU and RyQ Ingeniería 1989) by the Ministry of Housing and Urban Development through a World Bank loan. In 1992, the tool SAMPU was developed (CIS and MINVU 1992), which is the computer program based on MANVU methodology, and SAMPU was used until 1999 for some regions in Chile.

Currently, the available program is a simplified version of SAMPU called MANVUSIMP (MINVU 1999), which includes components such as Technical Evaluation, Performance Models, Maintenance Strategies and Economic Evaluation. However, these components have the following limitations:

- The general approach is for the project level rather than network level.
- The Technical Evaluation does not consider automated methodologies for data collection.
- The serviciability index used for condition evaluation consider as an important characteristic the roughness; then, .the analysis and calibration considering other distresses present in urban environment is needed for its application
- The Maintenance Strategies do not include current technologies for maintenance and rehabilitation treatments and preservation activities.
- The Performance Models have been adopted from foreign conditions, HDM2 and HDM3 for asphalt and Brokaw for concrete pavements (CIS and MINVU 1992). These models were adopted but not adapted for local condition neither adjusted over time with local performance data.
- The details of the Economic Evaluation are unknown.
- Due to these limitations, the professionals in charge of the pavement management usually decided the M&R activities based on their own experience rather than the information generated by the tool. Additionally, in some municipalities, the decisions about M&R treatments are based on the complaints of the users. This situation leads to a prioritized list of candidate projects based on the current condition of the pavement rather than on the life cycle assessment. Therefore, the process seeks to identify only the current network needs, which is a reactive approach.

Consequently, the available tool needs to be updated to increase its effectiveness for developing preservation, maintenance and rehabilitation standards and combining technical, economic, geographical, social and environmental aspects of urban streets to address a sustainable analysis.

- SGCPU – Concepción, Chile (Echaveguren T. and González D. 2000)

The PMS for the city of Concepción , Chile, called SGCPU (Sistema de Gestión de Conservación de pavimentos urbanos de Concepción) is based on the SAMPU.

This PMS includes the following components:

- Data base: Considers invariable information such as geometric characteristics of streets and variable data such as condition indicator and traffic.
- Sectioning: Considers the traffic data and the condition indicators for the definition of sections for the network
- Diagnosis: Includes the determination of condition and the application of pavement models. The indicators used for condition are the qualitative indices of cracking, roughness and serviceability. The performance models used are the Brokaw for concrete pavements, HMD-2 for semi flexible pavements and HMD-3 for flexible pavements. These two elements help the determination of the evolution overtime of the indicators without the application of maintenance standards in this component.
- Projects: This component generates the maintenance strategies for the sections based on a list of maintenance actions for concrete and asphalt pavements.
- Economic Evaluation: The strategies are evaluated based on their cost and the Vehicle Operating Model of the HDM-3
- Investment Program: Includes the prioritization of sections to be maintained. This analysis could be made based on difference parameters as serviceability, traffic, hierarchy and others.
- Update: In this component the data base is updated with the maintenance strategies applied as well as the project control and results.
- Software prototype: The system is supported by a software that works with the components.

This PMS is very complete but does not count with a combined index for urban pavements and the performance models used were calibrated for other conditions.

2.2 Pavement Condition Evaluation

Pavement condition is the one of the main input of the PMS. For this reason the requirements for objectivity and consistency are fundamental (Gordon K. 2008; TAC 2013).

Acquiring pavement condition data for network management can be an expensive and time consuming process. Given this, agencies have to be aware that the approach and methodology selected for surveying the network suits their individual goals and resources. Various pavement condition evaluation methodologies, using manual or automated collection techniques, have been developed to cope with this challenge (Kafi M. 2012; Wolters, A. et al. 2011).

2.2.1 Distresses

Distresses affecting asphalt pavements typically are classified in cracking, surface deterioration, patching and potholes, and miscellaneous distresses. Table 2-3 present an extensive list of distresses collected from the literature review (FHWA 2003b; de Solminihac 2001).

Likewise, distresses that affect concrete pavement are classified in cracking, joint deficiencies, surface defects, and miscellaneous distresses. Table 2-4 presents a list of concrete pavements distresses (FHWA 2003b; de Solminihac 2001).

Table 2-3 Distresses in Asphalt Pavements

Distress	Description
Fatigue Cracking	Series of interconnected cracks caused by fatigue failure of the asphalt surface (or stabilized base) under repeated traffic loading.
Transverse Cracking	Cracks perpendicular to the pavement's centerline or laydown direction. Usually a type of thermal cracking.
Block Cracking	Interconnected cracks that divide the pavement up into rectangular pieces. Blocks range in size from approximately 0.1 m^2 to 9 m^2. Larger blocks are generally classified as longitudinal and transverse cracking. Block cracking normally occurs over a large portion of pavement area but sometimes will occur only in non-traffic areas
Joint Reflection Cracking	Cracks in a flexible overlay of a rigid pavement. The cracks occur directly over the underlying rigid pavement joints.
Wheel Path Longitudinal Cracking	Cracks parallel to the pavement's centerline in the wheel path. It is a type of fatigue cracking.
Non-Wheel Path Longitudinal Cracking	Cracks parallel to the pavement's centerline outside the wheel path.
Edge Cracking	Applies only to pavements with unpaved shoulders. Crescent-shaped cracks or fairly continuous cracks which intersect the pavement edge and are located within 0.6 m of the pavement edge, adjacent to the shoulder. Includes longitudinal cracks outside of the wheel path and within 0.6 m of the pavement edge
Slippage Cracking	Crescent or half-moon shaped cracks generally having two ends pointed into the direction of traffic.
Bleeding	A film of asphalt binder on the pavement surface. It usually creates a shiny, glass-like reflecting surface that can become quite sticky
Corrugation and Shoving	A form of plastic movement typified by ripples (corrugation) or an abrupt wave (shoving) across the pavement surface. The distortion is perpendicular to the traffic direction. Usually occurs at points where traffic starts and stops (corrugation) or areas where HMA abuts a rigid object (shoving
Depression	Localized pavement surface areas with slightly lower elevations than the surrounding pavement
Polished Aggregate	Areas of HMA pavement where the portion of aggregate extending above the asphalt binder is either very small or there are no rough or angular aggregate particles.
Patch/ Patch Deterioration	An area of pavement that has been replaced with new material to repair the existing pavement. A patch is considered a defect no matter how well it performs.
Potholes	Small, bowl-shaped depressions in the pavement surface that penetrate all the way through the HMA layer down to the base course
Raveling	The progressive disintegration of an HMA layer from the surface downward as a result of the dislodgement of aggregate particles.
Rutting	Surface depression in the wheelpath. Pavement uplift (shearing) may occur along the sides of the rut. There are two basic types of rutting: mix rutting and subgrade rutting. Mix rutting occurs when the subgrade does not rut yet the pavement surface exhibits wheelpath depressions as a result of compaction/mix design problems. Subgrade rutting occurs when the subgrade exhibits wheelpath depressions due to loading.
Stripping	The loss of bond between aggregates and asphalt binder that typically begins at the bottom of the asphalt layer and progresses upward
Lane-to-Shoulder Dropoff	Difference in elevation between the pavement surface and the outside shoulder. Typically occurs when the outside shoulder settles as a result of pavement layer material differences.
Water Bleeding and Pumping	Water bleeding occurs when water seeps out of joints or cracks or through an excessively porous asphalt layer. Pumping occurs when water and fine material is ejected from underlying layers through cracks in the asphalt layer under moving loads.

Table 2-4. Distresses in Concrete Pavements

Distress	Description
Corner Breaks	A portion of the slab separated by a crack, which intersects the adjacent transverse and longitudinal joints, describing approximately a 45-degree angle with the direction of traffic.
Durability Cracking	Closely spaced crescent-shaped hairline cracking pattern. Occurs adjacent to joints, cracks, or free edges; initiating in slab corners. Dark coloring of the cracking pattern and surrounding area.
Longitudinal Cracking	Cracks that are predominantly parallel to the pavement centerline.
Transverse Cracking	Cracks that are predominantly perpendicular to the pavement centerline
Oblique Cracking	Crack that join the transverse joint with the longitudinal joint or union shoulder-slab. Occurs due to fatigue, beginning and ending at right angles in the central third of the transverse or longitudinal edge of the slab.
Transverse Joint Seal Damage	Transverse Joint seal damage is any condition which enables incompressible materials or water to infiltrate the joint from the surface through transverse joints.
Longitudinal Joint Seal Damage	Longitudinal Joint seal damage is any condition which enables incompressible materials or water to infiltrate the joint from the surface through longitudinal joints.
Spalling of Longitudinal Joints	Cracking, breaking, chipping, or fraying of slab edges within 0.3 m from the face of the longitudinal joint
Spalling of Transverse Joints	Cracking, breaking, chipping, or fraying of slab edges within 0.3 m from the face of the transverse joint.
Map Cracking	A series of cracks that extend only into the upper surface of the slab. Larger cracks frequently are oriented in the longitudinal direction of the pavement and are interconnected by finer transverse or random cracks.
Scaling	Scaling is the deterioration of the upper concrete slab surface, normally 3 mm to 13 mm, and may occur anywhere over the pavement.
Polished Aggregate	Surface mortar and texturing worn away to expose coarse aggregate.
Popouts	Small pieces of pavement broken loose from the surface, normally ranging in diameter from 25 mm to 100 mm, and depth from 13 mm to 50 mm
Blowups	Localized upward movement of the pavement surface at transverse joints or cracks, often accompanied by shattering of the concrete in that area.
Faulting	Difference in elevation across a joint or crack.
Lane-to-Shoulder Dropoff	Difference in elevation between the edge of slab and outside shoulder; typically occurs when the outside shoulder settles.
Lane-to-Shoulder Separation	Widening of the joint between the edge of the slab and the shoulder.
Patch/ Patch Deterioration	A portion or all of the original concrete slab that has been removed and replaced, or additional material applied to the pavement after original construction.
Water Bleeding and Pumping	Seeping or ejection of water from beneath the pavement through cracks. In some cases, detectable by deposits of fine material left on the pavement surface, which were pumped from the support layers and have stained the surface.

2.2.2 Condition Indexes

Among the various available evaluation methods, performance indicators that represent the current condition of pavement sections have demonstrated to be effective and reliable for managing road networks (ASTM 2003a; Chamorro et al. 2009b; Reza, F. et al. 2006; de Solminihac et al. 2009).

Agencies commonly use deterioration indices for network level decision making, which may combine different types of surface distresses, serviceability and structural indicators (Kafi M. 2012).

Two main methodologies were used to define the indices available in the literature: a methodology based on the use "master curves" that considers the type of distress, severity and density to determine the overall condition of the pavement; and a methodology based on the subjective evaluation of an expert panel, obtained based on surveys or in field evaluations, using statistical tools to transform the subjectivity associated to expert evaluations to objective evaluation of the pavement condition (Dictuc S.A. 2006).

Table 2-5 and Table 2-6 present some indices of both methodologies with the type of distresses considered and their equations for asphalt and concrete pavements. These indices differ in the types of distresses and criteria considered to quantify severity and density of distresses.

The Pavement Condition Index (PCI) is based on master curves, making cumulative reductions to a value that represents an excellent condition of pavements (PCI=100), based on the severity and density of measured distresses. The deduct values are calculated for each type of distress and the maximum deduct value is determine to use for the reduction of the excellent condition (Dictuc S.A. 2006). The PCI is worldwide used and considers a broad list of distresses, what are advantages of its adoption for application in different conditions; however, it was firstly developed for airports so the master curves need an adjustment and calibration for its use in urban pavements.

The other indices PQI, DMI, ICP and PSI showed in the tables above are based on expert panel evaluations. As it observed, different distresses are considered for asphalt and concrete; presenting all of them less options of distresses than the PCI. These indices were developed for interurban road networks (highways, express corridor, etc.); therefore, their direct application to urban networks (streets, avenues, etc.), is not representative and requires calibration and validation. However, the methodologies used in the calibration and validation are good options to apply for modeling an index for urban pavements.

Finally, the Serviciability Index (p) showed in the tables above, is an index developed for urban pavement networks based also on expert panel evaluations; however, does not consider some distresses important to analyze in urban environment, such as potholes, faulting, and utility cuts, and consider as the main condition the ride quality, which is not very influence in condition of urban pavements. Therefore, this index need an adjustment and calibration for its application in urban pavement networks.

The key to the development of an index to the condition of pavements is to recognize the subjective nature of the problem and associated techniques to quantify subjective information. The methodology is transferable but not models, so it must be calibrated for each agency (de Solminihac 2001).

Table 2-5. Performance Condition Indices - Asphalt

Pavement Condition Indices	**Ride Quality/ Roughness**	**Cracking**	**Patching and Potholes**	**Surface Deterioration**	**Other Distresses**	**Method**
Pavement Condition Index (PCI) (ASTM 2008)	Ride Quality	Fatigue Block Edge Longitudinal/ Transversal Reflection Slippage	Patch Deterioration Potholes	Rutting Shoving Bleeding Polishes Aggregate Raveling Depressions Corrugations Swell	Bumps and Sags Lane/Shoulder Drop off Railroad Croosing	Based on Master Curves
	PCI = C-∑ ∑ a (Ti, Sj, Dij) ×, Dij) x F; PCI = 100 CDVmax T: Distresses, S:Severities, D: Densities; F: Factor of adjustment for quantity of distresses CDVmax: Maximum Deduct Value					
Pavement Quality Index (PQI) (Haas et al. 1994)	RCI	SDI	SDI	SDI	SAI	Based on Expert Panel Evaluation
	PQI = 1.1607 + (0.596*RCI * SDI) + (0.5264 * RCI * Log 10 SAI) RDI: Riding Condition Index, SDI: Surface Distress Index, SAI: Structural Adequacy Index					
Distress Manifestation Index (DMI) (Chamorro et al. 2009b)		Fatigue Longitudinal Wheel Path Longitudinal No Wheel Path Transversal		Rutting		
	DMI_{NL}=10- 0.117 Fatigue (%) – 0.133Rutting (mm) - 0.157 Long Wheel Path (%)- 0.035Long Non Wheel Path (%) - 0.01Traversal (%)					
Pavement Condition Index (ICP) (Dictuc S.A. 2006)	IRI	Fatigue Linear	Potholes	Rutting Bleeding		
	ICP = 10.5 – 0.56IRI – 0.078 Rutting – 0.068 Potholes – 0.052 Fatigue – 0.031Bleeding – 0.026Linear Cracking					
Present Serviceability Index (PSI) (AASHTO 1993; de Solminihac 2001)	Slope Variance	Cracked surface	Patched surface	Rutting		
	PSI = 5.03 – 1.91 log (1+SV) – 0.01 (C+P) ^ 0.5 – 1.38 RD^2 SV: Slope Variance, C: Cracked surface, P: patched surface, RD: Rutting					
Serviciability Index (p) (MINVU 1999)	Ride quality	Cracking Index		Rutting		
	P= 5.8 – 0.8 C_1 – 0.1 C_2 – 0.3 C_3 C_1: Ride quality, C_2: Coefficient based on Cracking Index, C_3: Coefficient based on Rutting					

Table 2-6. Performance Condition Indices – Concrete

<table>
<tr><th>Pavement Condition Indices</th><th>Ride Quality/ Roughness</th><th>Cracking</th><th>Surface Defects</th><th>Joint Deficiencies</th><th>Other Distresses/Conditions</th><th>Method</th></tr>
<tr><td rowspan="2">Pavement Condition Index (PCI) (ASTM 2008)</td><td>Ride Quality</td><td>Corner Break
Divided Slab
Durability Cracking
Shrinkage
Linear</td><td>Polished Aggregate
Popouts
Punchout
Scaling, Map Cracking and Crazing</td><td>Joint Seal Damage
Spalling</td><td>Faulting
Blowup/Buckling
Pumping
Lane/Shoulder Drop-off
Railroad Crossing
Patch Deterioration</td><td rowspan="2">Based on Master Curves</td></tr>
<tr><td colspan="5">$PCI = C-\sum \sum a\ (Ti, Sj, Dij) \times, Dij)\ x\ F; PCI = 100\ CDVmax$
T: Distresses, S:Severities, D: Densities; F: Factor of adjustment for quantity of distresses
CDVmax: Maximum Deduct Value</td></tr>
<tr><td rowspan="2">Pavement Quality Index (PQI) (Haas et al. 1994)</td><td>RCI</td><td>SDI</td><td>SDI</td><td>SDI</td><td>SAI</td><td rowspan="10">Based on Expert Panel Evaluation</td></tr>
<tr><td colspan="5">$PQI = 1.1607 + (0.596*RCI * SDI) + (0.5264 * RCI * Log\ 10\ SAI)$
RDI: Riding Condition Index, SDI: Surface Distress Index, SAI: Structural Adequacy Index</td></tr>
<tr><td rowspan="2">Distress Manifestation Index (DMI) (Chamorro et al. 2009b)</td><td></td><td>Corner Break
Longitudinal
Transversal</td><td>Spalling</td><td></td><td></td></tr>
<tr><td colspan="5">DMI_{NL}=10- 0.0267 Spalling(%)– 0.0088Long.Meand(%)- 0.0010 Trv(%)- 0.0182Corner(%)</td></tr>
<tr><td rowspan="2">Pavement Condition Index (ICP) (Dictuc S.A. 2006)</td><td>IRI</td><td>Slab Cracked</td><td></td><td>Joints and cracks condition</td><td></td></tr>
<tr><td colspan="5">ICP = 10.7 – 0.85IRI – 0.057 Slab Cracked – 1.001 Joints and cracks condition</td></tr>
<tr><td rowspan="2">Present Serviceability Index (PSI) (AASHTO 1993; de Solminihac 2001)</td><td>Slope Variance</td><td>Cracked surface</td><td></td><td></td><td>Patched surface</td></tr>
<tr><td colspan="5">$PSI = 5.41 – 1.80 \log (1+SV) – 0.09 (C+P) ^\wedge 0.5$
SV: Slope Variance, C: cracked surface, P: patched surface</td></tr>
<tr><td rowspan="2">Serviciability Index (p) (MINVU 1999)</td><td>Ride quality</td><td>Cracking Index</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">$P= 5.8 – 0.8\ C_1 – 0.5\ C_2$
C_1: Ride quality, C_2: Coefficient based on Cracking Index</td></tr>
</table>

2.2.3 Data Collection Methodologies

Some agencies have established well developed guidelines to standardize data collection methodologies, among these are: Flexible Pavement Condition Rating, Guidelines for Municipalities

(MTO 1989), Índice de Agrietamiento (MINVU 1999), Standard Practice for Quantifying Cracks in Asphalt Pavement Surface Provisional Protocol PP 44-01 (AASHTO 2001), Distress Identification Manual for the Long-Term Pavement Performance Program (FHWA 2003b), International Standard Practices for Roads and Parking Lots Pavement Condition Index Surveys (ASTM 2003a), Unpaved Roads Condition Index based on Objective Distress Measures (Chamorro et al. 2009a), Instructivo de Inspección Visual de Caminos Pavimentados (MOP 2010), Distress Manifestation Index for Network Level (Chamorro et al. 2009b).

To evaluate pavement condition, most agencies perform data collection activities in one or more of the following four main areas: surface distress, roughness, structural adequacy, and friction. However, almost all agencies have differences in quantifying both the severity and density of distresses (Kafi M. 2012).

While condition evaluation methodologies differ from agency to agency, the principles are the same. Condition evaluation should incorporate a reasonable amount of detail (TAC 2013):

- Type of distress: cracking, rutting, potholes, faulting, etc.
- Severity of the distress: typically classified in levels; low, moderate, high.
- Density: area or extend of the distress. Typically calculated based on sum of distress type and severity level divided by the length or area evaluated.

The methodologies may include the entire pavement surface or some statistical portion of the network. Condition evaluations can be conducted using manual, semi-automated and automated methodologies (TAC 2013).

2.2.3.1 Manual Data Collection

Manual data collection can be defined as the process where people are directly involved in the observation or measurement of pavement deterioration (Flintsch, G. and McGhee K. 2009). Distresses are assessed or measured from a moving vehicle, known also as windshield surveys, or by evaluators walking along the road. Manual surveys require a trained evaluator or a team of trained evaluators who are assessing the type, severity, and density of distresses (Kafi M. 2012; Smith, R. E. et al. 1996).

Manual evaluation methodologies are typically detailed in the evaluation instruction manuals. Many agencies have developed training and educational tools that provide consistent assessment guidelines. Another element of achieving consistency is the establishment of a set of control sections that can be used for training, calibration of equipment, and process validation and verification (TAC 2013). Due to practical limitations, manual condition evaluations are sometimes conducted on a representative subset of the entire network (TAC 2013).

When manual evaluations are performed with experienced evaluators have the advantage that distresses are collected in a realistic way. This is very convenience for the development of performance models. However, requires the investment of time and human resources for the data collection.

2.2.3.2 Automated and Semi-Automated Data Collection

Automated and semi-automated data collection can be defined as the process of acquiring data with the aid of technology, mostly based on image, acoustic or profile measures (Flintsch, G. and McGhee K. 2009). These technologies may be equipped altogether on a mobile van or separately on trailers attached to a vehicle. (Wolters, A. et al. 2011). Collected data is analyzed with the aid of automated or semi-automated software to report the pavement distress. Studies have demonstrated that automated data collection is a safe, quick and reliable method compared to manual data collection (Chamorro et al. 2009a; b; Kafi M. 2012; Smith, R. E. et al. 1996; Tighe S. et al. 2008).

Semi-automated distress evaluation methods incorporate manual raters using one of two approaches to eliminate rater exposure to traffic: windshield surveys or survey based on pavement image review and rating (TAC 2013).

Automated distress evaluation methods based on images are challenged by complexities associated with image post processing, analysis and the requirement of correctly appropriate contrast/colour based thresholds for varying road surface colors and types (TAC 2013). However, studies have demonstrated existing technologies that improve considerably crack detection (MTQ 2005).

The big advantage of automated and semi-automated methodologies is the versatility of the data collection; however, good confidence of the results for some types of distresses is still not possible with current technologies. A perfect balance is to mix automated and manual methodologies to achieve good results and optimize resources in the data collection.

2.3 Performance Models

2.3.1 Modeling Methodologies

Performance models can be broadly classified as (TAC 2013):

- Deterministic: Shows the most common path of deterioration over time.
- Probabilistic: Quantifies some of the variability observed in the rate of deterioration from year to year

Both types of models are used to describe the expected performance over time. Pavement performance can be estimated using various techniques, from expert modelling using the opinions of experienced engineers to detailed performance prediction using historical data in a variety of deterministic and probabilistic mathematical models (Haas et al. 1994; TAC 2013):

- Mechanistic: The predicted measure is based on some primary response behavior such as stress or strain.
- Mechanistic–Empirical: Measured structural or functional deterioration is related to a response parameter.
- Empirical: The dependent variable of observed or measured structural or functional deterioration is related to one or more independent variables such as age, distress condition, smoothness, axle load application, etc.
- Probabilistic (or subjective): Experience is captured in a formal or structured way using probabilistic tools.

Probabilistic methods are good candidates to develop performance models for network management. Table 2-7 shows a summary of probabilistic methods to develop the performance models with their advantages and disadvantages (Chamorro 2012; Tighe S. 1997).

Bayesian models and Markov Chain models present good options to be applied when no historical data is available, but the latter is easier to apply for modeling nonlineal relationships.

Table 2-7. Probabilistic Modeling Methods

Modeling Method	Brief Description	Advantage	Disadvantage
Regressions	Statistical modeling method	- Simple modeling - Non lineal relations can be develop	- Efficient with large amounts of experimental data available - Cannot be extrapolate beyond the limits of the experimental data
Neural Networks	Simulate mathematical models of input parameters with outputs without model definition	- The process does not require a detailed relationship	- Complex modeling - Requires large amount of experimental data
Bayesian Models	Probabilistic modeling. It use Bayesian regressions (Prior Distributions+Data Collected)	- Objective with expert panel evaluations - Good results with small data base	- Complex modeling of Nonlineal relations
Markov Chain	Probabilistic modeling. With the use Probability Transition Matrix can predict future stages of pavement based on current stage	- Models can be developed without an historical data base - Simple to use for modeling Nonlineal relations	- Requires the development of Probability Transition Matrix for each combination of factors to be considered

2.3.2 Transition Matrices Techniques

A key aspect to apply Marcov Chain is the building of the transition probability matrices, which will determine the change of one state to another. Quite a few techniques are available to make up the transition matrices in order to perform the markov chain modeling. A summary of the main techniques is presented in Table 2-8 (Echaveguren T. 2006).

Table 2-8. Technique for Estimation of Transition Probability Matrices (Adapted from (Echaveguren T. 2006)).

Technique	Author	Aplication	Characteristics
Matrices Proportions and Inversions	(Tjan, A. and Pitaloka, D. 2005)	Pavement Distresses Modeling using PCI	Estimates the matrix directly from a equation of matrix regression. It requires a not singular matrix. It is equivalent to supervised training of MLP neural network
Minimizing the square error regarding class marks of each state, the expected value of the process, or proportion vectors of estimated and predicted value	(Ortiz-García, J. et al. 2006)		It is based on minimizing a squared error of an objective function. It requires abundant historical data for a good representation of the proportion vectors. Supports the analysis of stationary and non-stationary Markov chains. In contrast, deterministic methods are used to estimate the matrix.
Logistic model	(Ariaratnam, S. et al. 2001; Yang, J. et al. 2005)	Modeling of cracking in asphalt pavements. Assessment of infrastructure inspection needs	Analytically determination of the matrix from a mechanistic model. The model incorporates a logistic function. The transition matrix is obtained by minimizing the function of log - likelihood of the analytical matrices based on logistic functions.
Probit Model	(Baik, H. et al. n.d.)	Pavement Distresses Modeling using PCI	Similar case to the logistic model, changing only the functional specification of the transition matrix, under the hypothesis that the change in status is binary.
Bayesian Inference	(Micevski, T. et al. 2002; Tao, Z. et al. 1995)	Modeling of wáter colector distresses Brigde structural design	In this case it is obtained by Bayesian inference one probability density function (PDF) conditional retrospectively from a conditional a priori. Conditionality is given in terms of the parameters describing the FDP are conditioned by data describing a particular state.
Method based on Kernel	(Rajagopalan, B. et al. 1996)	Daily rainfall study	Estimates the transition probability matrix in a window of time estimated from the bandwidth of the kernel function. Subsequently estimates an FDP from proportions between two neighboring states calculated by the kernel function

The most feasible methods to apply in this research are those of (Tjan, A. and Pitaloka, D. 2005) and (Tjan, A. and Pitaloka, D. 2005). Both methods are based on the proportions approach.

2.3.3 Performance Models used for urban pavement management

Several performance models are available in the state-of-the-art and the-practice for different types of pavement conditions (AASHTO 1993; Arambula E. et al. 2011; Chamorro and Tighe 2011; Chan P. et al. 1997; Kargag-Ostadi N. et al. 2010; Mubaraki M. 2010; NCHRP 2010; Odartey L. et al. 2012; Rahim A. et al. 2013; Tack J. and Chou Y. 2001). In the following paragraphs some of the performance models used for pavement management at network level are commented:

- North Carolina’s Performance Models (Chan P. et al. 1997): North Carolina Department of Transportation (DOT) developed performance models for network-level project selection and prioritization for multiyear scheduling. These models were developed using the Pavement Condition Rating (PCR) of individual section as performance prediction through regression models.

- Network-Level Pavement Roughness Prediction Model for Rehabilitation (Kargag-Ostadi N. et al. 2010): A model for changes in the international roughness index (IRI) over time was developed through artificial neural networks (ANNs) pattern recognition. The ANN model was developed for asphalt pavement rehabilitation sections extracted from FHWA’s Long-Term Pavement Performance database in a wet–freeze climate and may be applied for similar conditions.

- Performance Prediction of the Present Serviceability Rating for Local Agencies in San Francisco Bay Area (Mok H. and Smith, R. E. 1997): Several local agencies in the San Francisco Bay Area use the Metropolitan Transportation Commission pavement management system that requires a pavement condition index (PCI) as the primary condition measure. However, several of these local agencies must also submit present serviceability rating (PSR) data on a sample of their network for use in the Highway Performance Monitoring System. Regression equations were developed to predict the PSR values, from PCI values. The local agencies using the Bay Area PMS can use these equations to estimate a PSR value from the inspection required for the PMS without inspecting pavement sections a second time.

- Performance Models for Flexible Pavements in Puerto Rico (Colucci B. and Ramírez-Beltrán N. 1997): These models were developed for flexible pavements of different climate conditions and functional classifications of highways in Puerto Rico, using the AASHTO performance equation as the base for PSI prediction. Delphi method, Levenberg-Marquardt, Weibull distribution and Monte Carlo simulation were conducted to determine the parameters of the equations for each group of pavements. This estimation scheme is useful for computing the remaining life for in-service pavements by following the methodology suggested in the AASHTO Design Guide for Pavement Structures.

- Performance Models for South Dakota (Jackson N. et al. 1996): The performance curves were developed by using both individual and composite pavement indexes for asphalt pavements. Regressions analyses were applied using expert opinion. The resulting pavement performance curves are adequate for the beginning input into the enhanced SDDOT PMS. The pavement performance curves developed should be revised as sufficient historical pavement condition data become available.

- Performance Models of PERS® software (Mubaraki M. 2010; PERS 2010): Material dependent models for predicting the pavement performance based on mechanistic (analytical) principles are used. The models estimate pavement performance in relation structural deterioration, rutting, roughness, skid resistance, and surface wear (Lund Z. 2009). In addition, empirical models are available, which can be calibrated automatically, and used as an alternative to the mechanistic models. The models were developed using the incremental-recursive mode by blending all the factors that are essential elements of the pavement deterioration process and enables the user to calibrate the models against historical data (Ullidtz, P. 1999).

- Performance Models of the Highway Development and Management Tool (HDM-3): (Bennett C. 1996; Mubaraki M. 2010): Includes deterministic mechanistic-empirical models based on roughness progression rediction methodology. The roughness progression is predicted as the sum of three components: structural deformation, surface condition, and an age-environmental-related roughness term. There are two models namely the incremental roughness model and the aggregate roughness model.
- Performance Models of Highway Development and Management Tool (HDM-4) (Mubaraki M. 2010): It was developed to provide additional capabilities such as models for traffic congestion, climate effects, safety and environmental effects that are not in HDM-3. The road deterioration models in HDM-4 are also deterministic in nature and are used for predicting annual conditions of roads as well as part of the inputs into user effects. Eight separate distress models, which can be divided into three categories: surfacing distress types including; cracking, raveling, potholing, deformation distress types including; rutting, and roughness, and surface texture distress types including; texture depth and skid resistance. These models predict the change of distress over a period using either time or traffic as the basis for pavement deterioration using the incremental methods. However, cracking and rutting as the commonest distress models in bituminous pavements. This method is the same as the incremental recursive method adopted in PERS. It allows the models in HDM-4 to analyze the various forms of distress types that could arise from pavement deterioration.
- Performance Models of the Australian Road Research Board (ARRB) (Mubaraki M. 2010): It has developed two distinctly different roughness progression model types, the network model and the project model. The network model is intended to undertake broad network analysis to arrive at annual maintenance budgets for certain roughness limits and provide maximum life cycle benefits. The ARRB developed another roughness progression model, rather than simply calibrating HDM-3, because HDM-3 does not directly address the influence maintenance practices has on pavement (Martin T. 1996).
- Concrete Pavement Models in Texas (Mubaraki M. 2010; Robinson C. et al. 1996): The following models were developed for the following distress types in Continuously Reinforced Concrete Pavement (CRCP): Portland cement concrete patches, asphalt patches, serviceability loss as measured by loss of ride score, transverse crack spacing, and crack spelling. Preliminary models are available for the following distresses in Jointed Concrete Pavement (JCP) and Jointed Reinforced Concrete Pavement (JRCP): patches, comer breaks, faulted joints and cracks, spalled joints and cracks, transverse crack spacing, and slabs with longitudinal cracks. A sigmoid regression equation was used for all distress types. These models are applicable only to non-overlaid Portland cement concrete pavements and are based on an upper limit of fifteen years for CRCP and sixteen years for JCP. The models represent the most accurate regression possible using the sigmoid equation with the available data.
- Performance Models for urban pavements (Mubaraki M. 2010): Models of PQI and Distress Maintenance Rating (DMR) were developed. Regression analysis were carried out, resulting

the exponential and polynomial function have good fitness with general data trends for the PQI (Shiyab A. 2007). Power and sigmoid form resulted better for overlays, modeling the DMR overtime (Adel W. et al. 1996).

- Performance Models of the Washington Department of Transportation (WSDOT) (Mubaraki M. 2010; WSDOT 1988): Empirical models were developed for PCR in the network level PMS.
- Performance Models of the Nevada Department of Transportation (NDOT) (Mubaraki M. 2010; Sabaaly, P. et al. 1996): A set of performance models for the network level of the PSI for monitoring the performance of overlays, using multilineal regressions.
- Brampton Performance Models in Canada (Mubaraki M. 2010; Phang, W. and Stott, G. 1981): The progression of specific distresses was performed to determine the Distress Manifestation (DM) assigned to a pavement at any time for asphalt pavements.
- Many PMS software used for network level analysis apply performance models developed for specific distresses to analysis de progression of deterioration; then, calculate the overall indices at different pavement ages such as Road Matrix, HPMS and dTims (Deighton 2012; Stantec 2009).

The models mentioned above were developed for combined indices of interurban pavements (highways, express corridor, etc.) or their main focus has been the progression of specific distresses overtime as a project level analysis to calculate after the overall condition of pavements at a certain time for network level management. Therefore, their direct application to urban pavement networks (streets, avenues, etc.), requires adaptation and further calibration and validation (Osorio et al. 2014). In addition, the tool Manusimp and Sampu (CIS and MINVU 1992; MINVU 1999) that were developed for urban pavement management in Chile, consider in their analysis performance models for asphalt and concrete developed for other conditions without a previous adaptation.

2.4 Preservation, Maintenance and Rehabilitation

There are different types and levels of actions to cost-effectively maintain the pavement infrastructure at an appropriate level of service. Description of type and levels of actions as well as the activities included within them vary from agency to agency, such as: emergency, routine, reactive, minor and major maintenance, preventive maintenance, corrective maintenance, preservation, restoration, rehabilitation and reconstruction (TAC 2013).

Typically, there are four broadly levels of maintenance in the literature review: routine maintenance, preservation, maintenance and rehabilitation. Routine maintenance are reactive and will often comprise relatively inexpensive, corrective types of actions to immediately address specific problems that may compromise the safety of road users. Preservation treatments are proactive, consisting of well-timed and executed activities to prevent premature distresses and to slow the rate of deterioration. Maintenance treatment could include minor non-structural activities and corrective activities. Rehabilitation consists of structural enhancements that renew the service life of an existing pavement and improve its load carrying capacity (TAC 2013).

Table 2-9 present an example of three types of maintenance and the activities included within them for asphalt and concrete pavements. In this example the treatments are presented in three categories: routine maintenance, preservation and rehabilitation, where preventive and corrective maintenance treatments are included as preservation.

Table 2-9. Routine maintenance, preservation, and rehabilitation activities (TAC, 2013)

Action Type	Maintenance activities	
	Asphalt Pavements	**Concrete Pavements**
Routine Maintenance	• Pothole Repair • Shallow Patching • Drainage Improvement	• Partial-Depth Slab Repair • Full-Depth Slab Repair • Drainage Improvement
Preservation	• Crack Sealing • Spray Patching • Full-Depth Patching • Heater Scarification • Hot In-Place Recycling • Cold In-Place Recycling • Full-Depth Reclamation • Thin Asphalt Overlay • Resurfacing-Fuctional • Milling and Resurfacing-Functional • Bonded Concrete Overlay • Slurry Sealing • Seal Coat • Microsurfacing	• Crack and Joint Sealing • Diamond Grinding • Shot Blasting • Partial-Depth Slab Repair • Full-Depth Slab Repair • Load Transfer Retrofit • Crack and Joint Stitching • Bonded Concrete Overlay • Slab Stabilization/Slab Jacking • HMA Overlay
Rehabilitation	• Resurfacing-Structural • Milling and Resurfacing-Structural • Bonded Concrete Overlay • Unbonded Concrete Overlays • Full-Depth Reclamation	• Bonded Concrete Overlay • Unbonded Concrete Overlay • Crack, Seat and Resurfacing • Rubblization and Resurfacing • HMA Overlay

Each agency needs to define the types and levels of maintenance actions suitable for them, as well as the boundary between them and the minimum acceptable level for their networks.

Good pavement management depends on the adoption of suitable defined standards which respond to the demands of users and minimize the total cost of the road comprising the costs of construction, maintenance and operation. Therefore, it is essential to establish a system of priorities for intervention decisions. Set thresholds for treatments application consist of define the thresholds above which should be applied an action. These thresholds are used to indicate which part of the network and which sections of the road are not meeting the objectives set. Each agency needs to define the thresholds for treatments application based on their strategies and network characteristics.

In Appendix I an extend list of maintenance treatments are presented for asphalt and concrete pavements.

2.5 Definitions Adopted

The terminology used to express the various maintenance types and practices is not unique, and thus, in this section we define the concepts used throughout this research:

- P&M&R actions: A treatment or set of treatments applied to a pavement to address the deterioration affecting its condition at a given time.
- Strategies: The set of maintenance actions applicable to a pavement during its life cycle, with the goal of improving its functional and/or structural condition.
- Policies: Define which criteria will be applied to the maintenance actions. These can be periodic throughout the time period for the application of maintenance actions; policies may also be response based, i.e., based on thresholds that trigger the need for a maintenance action (e.g., thresholds based on the UPCI for network management).
- Standards: This term refers to maintenance strategies to which a given policy is assigned, in terms of time frames or by response, during the life cycle of the pavement given its weather and hierarchy (structure and transit).
- Types of P&M&R actions: This term refers to the grouping of the actions and treatments based on the characteristics of their application. Three types are defined for this research: Preservation, Maintenance and Rehabilitation.
- Preservation: This term includes preservation and functional maintenance actions, covering actions that improve the pavement functionality, extending its useful life without improving their structural capacity (FHWA 2014). These actions are applied before significant deterioration appears, on pavements of good or acceptable condition.
- Maintenance: This term includes actions that improve the structural capacity of the pavement, considerably extending its useful life and/or increasing its structural capacity (FHWA 2014). These actions are applied to pavements of regular or poor condition.
- Rehabilitation: This term includes pavement reconstruction actions that are performed when the pavement is in very poor condition.

In addition, Figure 2-1 presents the interactions between the definitions presented above.

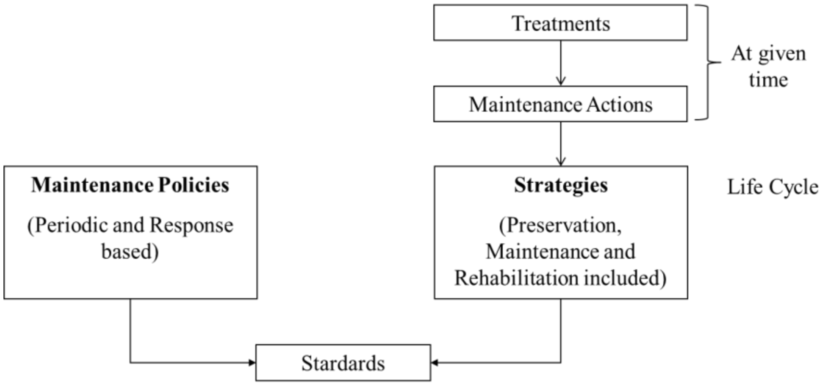


Figure 2-1. Interactions between maintenance definitions

2.6 Urban Pavement Maintenance in Chile

Chile is a developing country with an emerging economy. The larger urban pavement network is located in the capital, Santiago, with 9,060 km of streets (MINVU 2012).

Urban pavements in many cities often provide users with an overall bad condition of the network, which results in negative impacts on the population and economy of the country. These problems in Chile have two main causes: the regulations are not clear on the financial and administrative responsibilities of the organizations in charge of the urban pavement management, and a sustainable management system to facilitate the decision process is not available (PUC 2010).

Details about the existing tool for urban management were mentioned in previous section.

The current institutional management framework (MINVU 2012) for urban pavement maintenance in Chile can be observed in the following in the left side of Figure 2-2. The law confers obligations related to urban pavement management to:

- The Municipalities
- The Ministry of Housing and Urban Development (MINVU) and the Ministerial Regional Secretariat (SEREMI) through the Regional Housing and Urban Services (SERVIU), the Regional Governments and the National Funds for Regional Development (FNDR) for the urban pavement networks
- The Ministry of Transportation and Telecommunications (MTT) through the Transantiago for the streets where public buses drive along.
- The Ministry of Public Works (MOP) through the Regional Direction of Roads, for the streets declared public. Additionally, the metropolitan region has special responsibilities attributed to the Municipality of Santiago, which has autonomy for managing its network (PUC 2010).

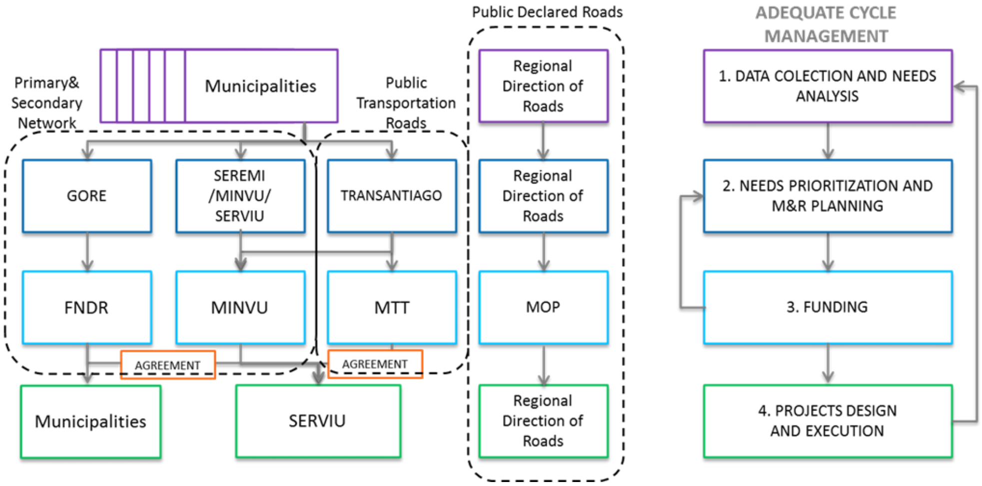


Figure 2-2. Current Institutional Management Framework (MINVU 2012)

If this institutional framework is compared with an adequate cycle management that is on the right side of Figure 2-2, the following can be observed:

- The data collection and needs analysis are not legally assigned to the municipalities or other institutions.

- For the needs prioritization, M&R Planning and Funding, there are many institutions responsible for urban planning and road maintenance that have been legally established but their functions are developed in an uncoordinated form, which makes it difficult to carry out proper pavement management (PUC 2010).
- The project execution needs special agreements to be developed, which makes the process extremely slow.
- There is no feedback to all of the processes from the M&R project that has been executed.

This occurs because the legislation does not specify how the maintenance actions have to be coordinated, executed and prioritized to optimize the assignment of resources for pavement maintenance.

Due to the current administrative structure, the budget for maintenance actions is not totally exploited annually for lack of decision making. Therefore, the institutional framework needs an adjustment to make possible an implementation of an urban pavement management system.

2.7 Limitations of the Current State-of-the-art and the-practice, and Opportunities for Improvement

Different tools are available in the state-of-the-art and the-practice for pavement management. However, their development was based mainly on interurban pavement conditions. Consequently, their proper application for managing urban pavement networks in developing countries presents the following limitations and opportunities for improvement:

- **Available PMS:** Several PMS tools are available but they do not suit the urban pavement network management needs. Adjustments for their application involve great efforts and resources, especially in developing countries. The opportunity for improvement is the development of technical tools to be integrated in a sustainable management system to facilitate the decision process for urban pavement networks can be easily adapted and implemented by different agencies in developing countries.
- **Pavement Condition Evaluation:** Several pavement condition indices are available; however, those indices were developed for interurban road networks (highways, express corridor, etc.); then, their application to urban pavements (streets, avenues, etc.) is not representative and requires calibration and validation. Moreover, considering developing countries, economic resources for semi-automated or automated evaluations are not always available; therefore, an evaluation methodology considering manual or automated field evaluation is needed. The opportunities for improvement is the calibration and validation of pavement condition evaluation for urban network management in developing countries, considering evaluation guidelines for manual and automated data collection.
- **Performance Models:** Several performance models found in the literature review have been developed for particular distresses, and some of them for pavement condition indexes of interurban pavements. Therefore, their application for urban pavement conditions need recalibration and validation. The opportunities for improvement are the calibration and validation of performance models for urban pavement condition indexes, adaptable to different climates and road uses.

- **P&M&R Standards:** Available P&M&R standards include some maintenance activities not appropriate for urban conditions as well as are their applications thresholds are define based on particular distresses or pavement condition indexes for interurban pavements, and their performance models. Consequently, they are not adoptable for direct use in urban pavements. The opportunity for improvement is the definition of maintenance standards for urban pavements including sustainable maintenance activities based on the urban pavement condition indexes and their performance models.

Chapter 3

Urban Pavement Management Framework

In this chapter, a Framework for Urban Pavement Management is presented considering sustainable criteria.

The first version of this framework was presented at the 1st International Specialty Conference on Sustaining Public Infrastructure, Canadian Society of Civil Engineers, Canada (Osorio et al. 2012).

3.1 Research Project about Urban Pavement Management

This thesis is part of a three-year project being developed by the Pontificia Universidad Católica de Chile (PUC), Chile. The project is called Fondef D09I1018 "Investigación y Desarrollo de Soluciones para la Gestión de Pavimentos Urbanos en Chile" (Research and Development of Solutions for Urban Pavement Management in Chile).

This project is being funded by the Chilean Government though Fondef – Conicyt, the PUC, and the associated institutions: the Ministry of Housing and Urban Development (MINVU), the Regional Government for the Metropolitan Region (GORE), the Municipality of Santiago and the Municipality of Macul. An external collaborator in the project is the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, Canada.

The overall project resulted in a cooperative initiative of the PUC and funding partners to accomplish the current and future needs of urban pavements and provide their effective management via the development of practical tools to assist agencies in decision-making related to the management of urban networks (PUC 2010).

The project focuses on the development of an UPMS for Chile with the main goal of covering the limitations found in the-state-of-the-art and the-practice presented in the literature review. The overall objective is the development of all an Urban Pavement Management System for Chile considering the components for the network level analysis aforementioned (PUC 2010):

- Recommendations for institutional adjustments
- Urban Pavement Condition Evaluation
- Urban Pavement Performance Models
- P&M&R standards for Urban Pavements
- Optimization of P&M&R standards
- Prioritization based on sustainable criteria
- Integration with a Geographic Information System

Even though the project is being developed in Chile, the expected outcomes, such as technical tools and the resulting Urban Pavement Management System, may be adapted and adopted in other countries for urban pavement management.

The research performed for this doctoral thesis delivered its results about the urban pavement condition evaluation, performance models and recommendation for P&M&R standards for their integration in the UPMS underdevelopment in this project.

3.2 Proposed Framework

This project involves the development of Urban Pavement Management Framework that was developed by the team research project, which combines all important and relevant aspects in a long term analysis approach. These aspects are technical, economic, geographical, social, political and environmental. The long term approach will be given through a life cycle cost analysis. This comprehensive approach is subsequently referred to as a sustainable urban pavement management framework (Chamorro 2012; Chamorro and Tighe 2009).

The proposed framework is presented in Figure 3-1and includes four types of components: sources or input data, evaluation methodologies, processes, and outputs. This framework proposes an iterative process for each year of the analysis period considered that starts in year i=1. In broad terms, the processes use the methodologies fed with the sources to deliver the outputs.

The research performed in this thesis is framed into the highlighted boxes of the Figure 3-1: Network condition, Performance Models and Optimal P+M+R Standards. For this latter component the scope of the results is only the recommendation of the maintenance standards, including application thresholds and effects on the pavement condition. The work carried out in the research also included the way of how the tools developed will be integrated in the proposed framework.

A description of each component is presented in the following subsection of this chapter.

3.2.1 Sources (Input Data)

Three types of data feed the system: inventory, network condition, and socio-political data. They are described in detail below.

Inventory

The inventory includes the information regarding: geometric data (length, transverse section, number of lanes and types of drainage); pavement type (asphalt, concrete or interlocking pavements); hierarchy (based on the functional classification, structure and traffic); climate (dry, Mediterranean and humid); and geographical information (which include georeferenced coordinates of the network streets).

Network Condition

The condition of the network includes the distresses collected in field, and the Urban Pavement Condition Index (UPCI) calculated by equations 1 to 4 presented in section 6.3. This is the first result of this research that is used in this framework.

Socio-political data

The socio-political data includes the following information: number of complaints made by the users for each analyzed section of the network; major health, education and emergency infrastructures; city blocks with census data; public transport routes; zones of touristic interest; commercial patents; and public policy strategy.

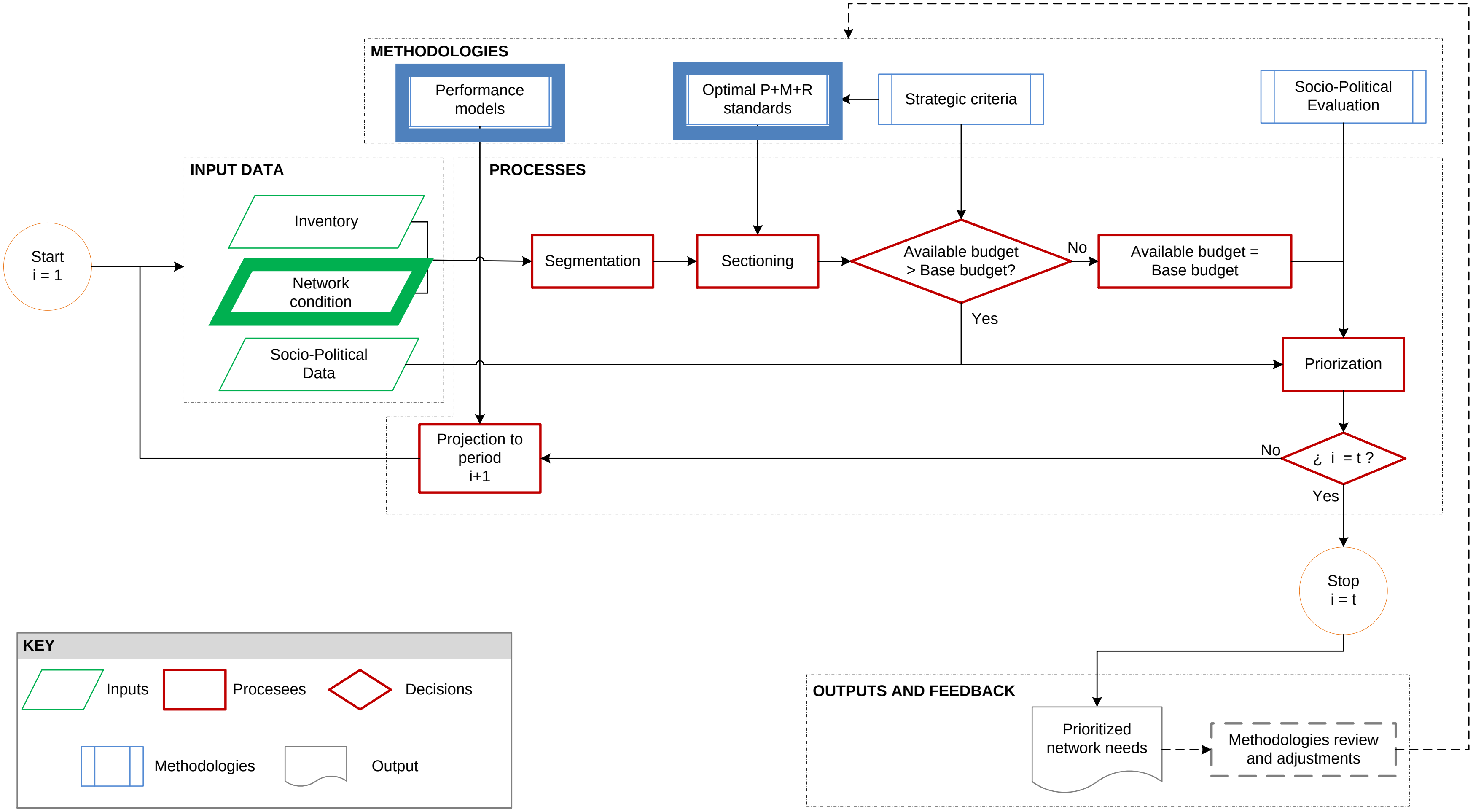


Figure 3-1. Sustainable Framework Proposed for Management of Urban Pavement Networks

All sustainable aspects to be considered in the UPMS must have a target associated at this level, and will include the prioritization and optimization criteria. Some of these targets are presented below:

- Technical: The acceptable threshold for the overall network and particular pavement sections will be defined, in terms of the UPCI.
- Economic: The economic parameters for the network analysis will be defined, such as period analysis, discount rate, etc.
- Environmental: The environmental policies such as the use of the environmental friendly techniques for the maintenance and rehabilitation treatments will be included.
- Social: The social aspects to be considered in the prioritization analysis at network level are included.
- Geographical: Criteria such as special proximity of the projects of the treatments will be considered.
- Available Budget: The economic constraints and budget available for urban pavement maintenance will be defined.

3.2.2 Methodologies

Four methodologies are applied to carry out the process of the system. These four methodologies are then tested as they are calibrated and validated into the system independently:

Performance Models

Pavement performance models were developed for the combination of different pavement types, climates and hierarchies as described in Section 7.2. The models developed in this research reflect the pavement deterioration over time as accurately as possible. This is the second result of this research that is used in this framework.

Optimized P&M&R Standards

The optimized P&M&R Standards includes two different methodologies: the P&M&R Standards and the Cost-Effectiveness evaluation.

The P&M&R Standards include the list of treatments available in the network area, their possible combinations, their estimated unit cost, their application thresholds and their effect on pavement condition (in terms of UPCI). These standards were achieved through the analysis of possible distresses, UPCI values, thresholds defined in the strategic criteria and performance models. Different options of treatments are included to be analyzed in the cost-effectiveness evaluation. This is the third result of this research that is used in this framework.

Cost-Effectiveness evaluation consists of the evaluation of P&M&R Standards at the section level. This evaluation is based on cost-effectiveness (CE), integrating thus economic and technical aspects in the assessment of maintenance alternatives.

The optimal treatments of P&M&R are defined from the cost-effectiveness analysis. In this component the current and future network needs are defined.

The main output of the analysis consists of the definition of P&M&R standard optimized to accomplish the technical threshold defined in the strategic level, based on analysis mentioned to apply in urban pavements.

Strategic Criteria

The strategic criteria include the overall goals and the institution policies and budget available for urban pavement preservation, maintenance and rehabilitation. The main goals and policies for urban pavement management practice in the short, medium and long term are defined within this data. The determination of these policies will be made by the authorities of the institutions in charge of the urban pavements.

Socio-Political Evaluation

Each socio-political criterion is evaluated using GIS's spatial analysis like the service area of a major infrastructure or intersects to evaluate the impact of a section in the population using the socio-political data. Then each section is compared with the rest of the sections of the network in order to give them a relative priority index for each criterion.

Finally each priority index is weighted in a polynomial that calculates the overall index of socio-political criteria called Socio Political Factor (SPF). The output of the analysis is the SPF for each section of the network and the display of a map that allows a better comprehension of the results.

3.2.3 Processes

Seven processes are included in the system with two decisions within them:

Segmentation

A dynamic segmentation of streets is performed based on the geometric data, pavement type and hierarchy information.

Then, a cumulate difference methodology will be carried out to calculate the segments based on their UPCI information. The average UPCI will be the representative of each segment.

Sectioning

Sections are defined based on: the segmentation carried out in the previous process, the technical thresholds of the strategic criteria and the optimized P&M&R Standards.

The sections defined in this processes result in the segments with the P&M&R treatments assigned. The list of these sections with theirs assigned P&M&R treatments will compose the network needs without budget constraint, which will be the output of this process.

Available Budget > Base Budget?

This decision box evaluates whether the Available Budget higher than the Base Budget calculated for Network Needs?

If the answer is "No": Insufficient budget is available to meet minimum requirements. This scenario occurs when the available budget is less than the cost required to meet the minimum requirements defined at strategic level. In this case, the system gives precedence to the requirements and objectives defined at the strategic level against the actual budgetary capacity analysis for the year and continue the analysis by considering a budget equal to the minimum. These shortcomings in the budget will be discussed in detail at the end of the analysis period so that revisions and adjustments to the strategic criteria will be proposed.

If the answer is "Yes": Sufficient budget is available to meet minimum requirements: In this case, the available budget is not less than the minimum required to meet the requirements defined at the strategic level. Therefore, no adjustment is necessary and the prioritization process begins without any budget adjustment.

Regardless of the existing budget scenario in the year of analysis, the following process to be performed is prioritization.

Prioritization

The network prioritization defines an ordered list of sections and their standards of P + M + R more suitable to keep the network with the available budget. The suitability of the sections and standards of P + M + R is defined by the available budget, optimized P&M&R Standards, technical and economic analysis, and socio-political evaluation methodology. This analysis will incorporate technical, economic, socio-political and geographical goals defined at the strategic criteria.

i = t ?

Once selected sections treated, it checks whether it have been analyzed each year (i) of the analysis period (t). In this case, two scenarios are considered:

- There have been analyzed each year of the analysis period (i <t): The process described above will be repeat considering the condition of the pavement in the new year of analysis (i + 1). This condition is derived from the methodology of performance models, which come preloaded on the SGPU.
- We analyzed each year of the analysis period (i = t): In this case, the selection of projects has been made for each year of the analysis period, so the iterative process stops.

3.2.4 Outputs

Finally, after analyzing all the years of the analysis period the system will be able to deliver the outputs from the processes considered in the framework.

The output of SGPU consisting of the prioritized needs of the network is obtained. In this output will be presented in detail the following information:

- Sections of the network to be treated in each year of the analysis period
- The standards of P&M&R to be applied
- The condition of the sections along the period of analysis
- Detailed costs associated with the resulting maintenance program.

The prioritized list of needs of the network is then subjected to a process of adjustment and revision of the methodologies used, so that there is a feedback process.

3.3 Chapter Summary

The UPM Framework considers various factors for managing urban pavements network. This Framework serves as a guide for the development of the UPMS underdevelopment within the project.

The research project is divided into three main areas of research: Institutional, Pavement Management and Geographic Information System (GIS).

The Institutional area is in charge of the analysis of current regulations for urban pavement management and the development of recommendations of institutional adjustments that facilities the implementation and use of the UPMS.

The proposed UPM Framework represents the way that tools developed independently in the areas of Pavement Management and GIS will be integrated into of the UPMS.

This thesis research is framed into the Pavement Management area and delivers its results for the highlighted boxes of the diagram showed in Figure 3-1.

Chapter 4

Experimental Designs and Data Collection

4.1 Introduction

As part of the development of this research, it was necessary to create experimental designs for data collection and analysis to develop the technical tools proposed in the thesis objectives:

1. Calibration and validation of an Urban Pavement Condition Index (UPCI), considering manual and automated data collection methodologies.
2. Calibrate and validate performance models for urban pavements representative to different climates, structures, traffic and pavement types.
3. Recommendation of maintenance standards for urban pavement condition.

The experimental designs were carried out considering observation experiments. In these cases the explanatory variables cannot be manipulated to induce variability and analyze its effect on the response variable, but it is possible to perform a controlled experiment. Therefore, the aim of the experimental designs was to identify enough data to organize the variables in levels allowing the adequate observation of the response variables.

Each experimental design is presented in the following paragraphs, where the dependent and independent variables are defined, the factorial design for the data collection and the methodology to be followed for the data collection.

4.2 Conceptual Models to calibrate and validate

Two models are calibrated and validated in this research. Figure 4-1 shows the components of pavement life cycle to better understand where the models addressed in the research act in this cycle.

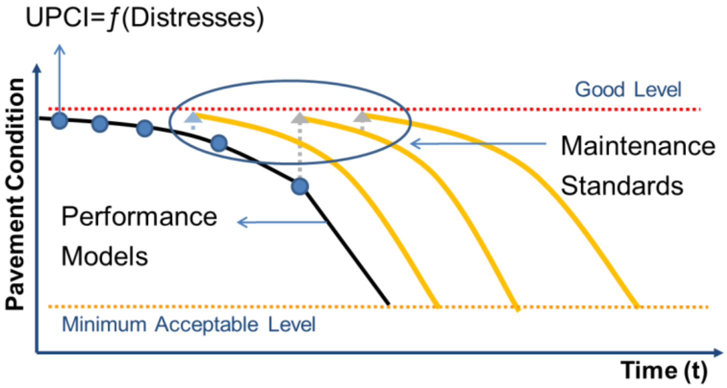


Figure 4-1. Components of pavements life cycle

The first model corresponds to the Urban Pavement Condition Index (UPCI) that represents the overall condition of a pavement at a specific point of the service life. The model analyzes a transversal frame in the time. Then, the UPCI is a function of the distresses present in the pavement at that time and the type of pavement analyzed.

The second model analyzes the deterioration of the UPCI overtime, which corresponds to the performance models. The model analyzes longitudinal view overtime. Therefore, considering the factors involve in pavement deterioration presented in Section 1.1, this model is a function of the pavement type, the traffic, the structure and the climate.

As a result of these two models, maintenance standards could be recommended, based on the UPCI and its performance models. This task requires the analysis of threshold of application and effect in the UPCI of each maintenance actions.

4.3 Experimental Design for the Calibration and validation of the UPCI

4.3.1 Variables, Factorial Design and Inference Space Definition

The dependent variable is the Urban Pavement Condition Index (UPCI), which represents the overall condition of urban pavements at a specific time due to the combined effect of the distresses in the pavement. The UPCI is defined as a numerical value on a scale from 1 to 10, with 1 being the worst condition and 10 the best. This number is also associated with a quantitative scale of five levels: very good, good, regular, bad and very bad, which represents the pavement conditions based on functional importance. The UPCI considered as the dependent variable is the UPCI Observed in the field by an Expert Panel. The expert panel was composed by experienced professionals in the pavement area.

The independent variables for the development of the UPCI are the distresses and the type of pavement.

In order to define the distresses to consider in the analysis, a broad universe of distresses was considered for each type of pavement, defined based on review and combination of various pavement evaluation guides (FHWA 2003b; MINVU 2008a, 1999; MOP 2010; MTO 1989).

Then, field observations were performed using a windshield evaluation in order to analyze the distresses most representative of the network. Sheets used for windshield evaluation are presented in Appendix A.

In Table 4-1 to Table 4-3, the distresses, levels of severity, and unit considered for evaluating in the field are presented. These distresses were chosen based on the analysis of the windshield evaluation.

The skid resistance was not considered based on the results of the projects Fondef D03I1042 and Fondecyt 1040335, from which it was determined that this property for concrete and asphalt pavement is beyond the scope of a network indicator due mainly to the characteristics of macrotexture and low speeds for these urban pavements.

The characteristics to evaluate each type of pavement are in terms of the severity and density of the distress. The first parameter indicates how severe the distress is and is evaluated on three levels: low, moderate and high. The second parameter indicates how expanded the distress is and is evaluated for the quantity of the measurements (Dictuc S.A. 2006; FHWA 2003b; MOP 2010).

Table 4-1. Distresses Considered for Asphalt Pavements

Distress of Asphalt Pavements	Levels of Severity	Unit
- Fatigue Cracking	Three	m^2
- Wheel Path Longitudinal Cracking	Three	m
- Non/Wheel Path Longitudinal	Three	m
- Reflection Cracking	Three	m
- Transverse Cracking	Three	m
- Patch Deterioration	Three	N°, m^2
- Potholes	None	N°, m^2
- Rutting	None	mm
- Shoving	None	N°, m^2
- Bleeding	None	N°, m^2
- Polished Aggregate	None	N°, m^2
- Raveling	None	N°, m^2
- Manholes and catchbasins	Three	N°
- Rughness*	None	m/Km

(*) Measured only with automated equipment

Table 4-2. Distresses Considered for Concrete Pavements

Distress of Concrete Pavements	Levels of Severity	Unit
- Corner Breaks	Three	N°
- Longitudinal Cracking	Three	m
- Transverse Cracking	Three	N°, m
- Oblicous Cracking	Three	
- Transversal Joint Seal Damage	Three	N°
- Longitudinal Joint Seal Damage	None	m
- Spalling of longitudinal joints	Three	m
- Spalling of transverse joints	Three	m
- Map Cracking	None	N°, m^2
- Scaling	None	N°, m^2
- Patch Deterioration	Three	N°, m^2
- Polished Aggregate	None	N°, m^2
- Manholes and catchbasins	Three	N°
- Faulting**	None	mm
- Rughness*	None	m/Km

(*) Measured only with automated equipment
(**) Measured only with manual methodology

Table 4-3. Distresses Considered for Interlocking Pavements

Distresses of Interlocking Pavements	Levels of Severity	Unit
- Block missing	None	N°
- Joint Damage	None	m
- Patch Deterioration	Three	N°, m^2
- Potholes	None	N°, m^2
- Manholes and catchbasins	Three	N°
- Skid Resistance*	None	Corrected BPN
- Longitudinal Cracking	Three	m
- Rughness*	None	m/Km

(*) Measured only with automated equipment

The factorial design for the development of the UPCI is presented in Table 4-4. It is proposed in a generic format due to the quantity of distresses considered for each pavement type and their interaction. The objective of this factorial matrix was to order the samples for selecting during the data collection in the field. The factorial has five factors: Pavement Type with three levels, distresses with different levels for each pavement type, distress severity with different levels depending on the type of distress, distresses density with one level, and UPCI_{OBS} with one level.

Table 4-4. Factorial Design for UPCI Calibration and Validation

<table>
<tr><td rowspan="2"></td><td colspan="27">Pavement Type 1</td><td colspan="3" rowspan="2">Expert Evaluator UPCI_{OBS}</td></tr>
<tr><td colspan="9">Distress I</td><td colspan="9">…</td><td colspan="9">Distress n</td></tr>
<tr><td>Severity</td><td colspan="3">Low</td><td colspan="3">Moderate</td><td colspan="3">High</td><td colspan="3">Low</td><td colspan="3">Moderate</td><td colspan="3">High</td><td colspan="3">Low</td><td colspan="3">Moderate</td><td colspan="3">High</td><td>1 - 2</td><td>…</td><td>9 - 10</td></tr>
<tr><td>Density</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

The factorial comprised thousands of possible scenarios for each pavement type; considering the interaction within distresses and their levels of severity. However, the factorial design filled up will be unbalanced representing the real distribution of distresses and their interaction observed in the field within the network evaluated.

The inference space of the factors describing the factorial design is the following:

- Pavement type: asphalt, concrete, and interlocking pavements
- Distresses: corresponding to the classification of Table 4-1, Table 4-2 and Table 4-3. Although the roughness is not a distress but a representation of distresses, in this factorial is considered as a distress only as a generic name.

- Distress severity: low, moderate and high for the distresses with three levels (See Table 4-1, Table 4-2 and Table 4-3). The limit values for severity levels were adopted from the Distress Identification Manual for the Long-Term Pavement Performance Program and the guide “Inspección Visual de caminos pavimentados del Ministerio de Obras Públicas de Chile” (FHWA 2003b; MOP 2010). The levels of severity of manholes for all types of pavements and cracking for interlocking pavements, which are not defined in these guides, were defined for this research.
- Distress density: is evaluated for the quantity of the measurements on three levels.
- $UPCI_{OBS}$: Pavement condition evaluated by the expert panel in a value between 1 and 10.

4.3.2 Sample size estimation

As the factorial for each pavement type comprise thousands of possible scenarios of distresses interaction, the estimation of the minimum quantity of scenarios to look for in the field in order to ensure the precision and accuracy of the regression coefficients. Finite population technique was used for determining the minimum quantity of scenarios based on confidence level and probability error (Dictuc S.A. 2006).

The following equation was applied to calculate the minimum quantity of scenarios:

$$n = \frac{n_o}{1 + \frac{n_o}{N}} \quad \text{donde} \quad n_o = Z^2 \cdot \frac{S^2}{e^2}$$

Where:
n = Minimum number of scenarios
Z = Normal area for the level of confidence chosen
S = Standard deviation
e = Expected error
N = Total possible scenarios

As this is a technique for finite populations delivers asymptotic results for big populations. For this reason, this analysis was performed considering a value of N equal to 1.000, resulting in a minimum number of scenarios of 24 with a confidence level of 95%, expected error of 10% and standard deviation of 0.3.

In Addition, three sections for each scenario were defined as the quantity needed to ensure the precision of the analysis.

4.3.3 Sample Unit Definition and Test Section Selection

To select a representative size for the sample unit to be used in the data collection, the functionality of the evaluations in the field was analyzed. One important factor to be considered is the speed and consistency of data collection. IRI was determined to be a critical evaluation as it is evaluated at constant speeds. For this reason, the length of the sample was chosen based on the minimum length to accelerate, evaluate and stop within one block. The width of the samples was defined as one lane.

The size of the sample unit for each pavement is defined as follows:

- Asphalt pavements: lane width x 50 m long, divided into 10-m segments. The lane widths vary from 2.80 to 4.50 m in Chilean urban streets.
- Concrete pavement: lane width x 10 slabs long, where each slab is a segment.

The subdivision of the segments is to facilitate the manual data collection in a shorter distance. All the distresses found in each segment are summed for the total distresses of the sample unit.

The data obtained for the sampling unit included the following:

- Distresses: presented in Table 4-1and Table 4-3.
- Inventory data: name of the road; type of pavement, width, length and traffic direction of the lane; reference and GPS tracking of the section.

The selection of sections to evaluate is performed according to the following criteria:

- Type, severity and density of the distresses
- Location of the streets

The first step for the section selection was a windshield evaluation, to collect the types, severity and density of distresses in streets of Santiago quickly. Sheets used for windshield evaluation are presented in Appendix A. Then, the final selection was done based on this information and the closeness of the streets selected.

4.3.4 Methodology for the Calibration and Validation of UPCI

The methodology prepared for the development of UPCI is presented in Figure 4-2 with the interaction between stages.

The methodology includes the stages to be followed to perform the data collection and analysis for the development of UPCI considering Manual and Automated evaluations. Every stage is described as follows:

1. Experimental Design to develop UPCI: Experiments for the calibration and validation of the condition indicator for urban networks were defined for manual and automated data collected, including: dependent and independent variables, development of distress evaluation guidelines, selection of an urban network, data collection and analysis methodologies.
2. Development of distress evaluation guidelines: Typical distresses observed in urban pavements were studied in detail. Based on the state-of-the-art and the-practice, research team experience and windshield evaluations performed in different urban networks, distresses were selected for the purposes of the study, considering manual and automated surveys.
3. Network selection: Different sections of asphalt and concrete pavements were selected from the network of the city of Santiago, Chile, including different functional categories, pavement structures, traffic types and traffic volumes.

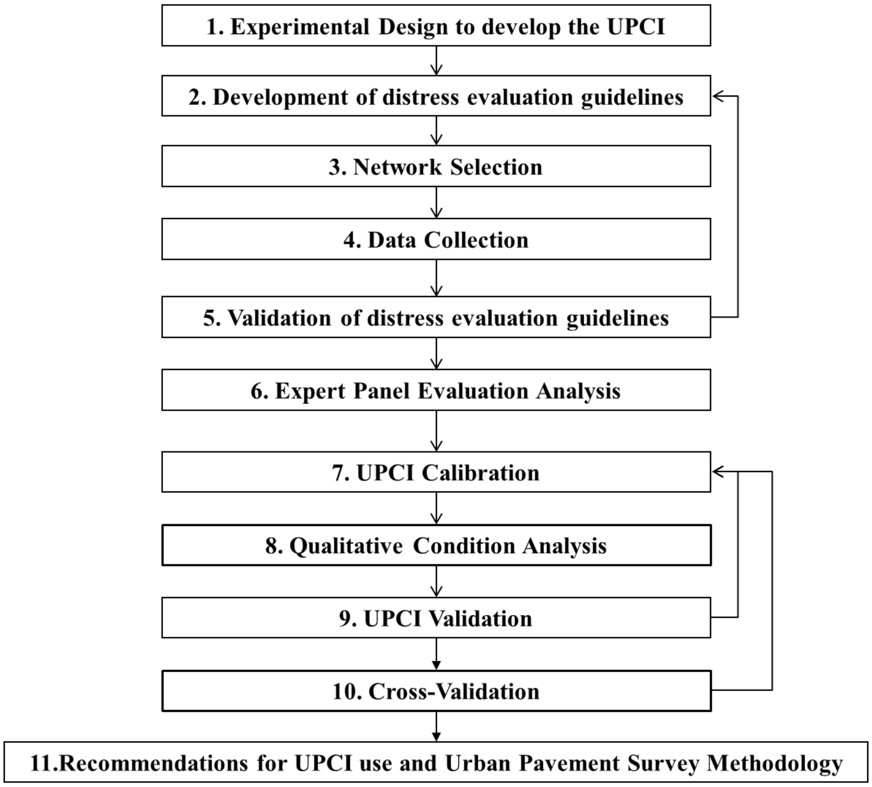


Figure 4-2. Methodology for Calibration of the Urban Pavement Evaluation Methodology

4. Data Collection: Surface distresses were assessed in the selected network following the evaluation guidelines for manual and automated data collection. In addition, an expert panel assessed the overall condition of the selected network. A first set of data was collected and processed in order to validate the distress evaluation guidelines. Then, a second set of data was collected for the calibration and validation of the urban condition indicator. An Expert Panel composed of experienced professionals in the pavement area evaluated the test sections, giving them a UPCI Observed ($UPCI_{OBS}$), which was considered as the dependent variable for the development of the UPCI

5. Validation of distress evaluation guidelines: Repeatability and reproducibility analyses were performed to check the reliability of manual and automated evaluations, and to validate the developed evaluation guidelines.

6. Expert Panel Evaluation Analysis: Paired sample T-Test analysis was performed to analyze the variability between evaluators, for each type of pavement.

7. Calibration of UPCI: Statistical analyses were made to the collected data for the calibration and validation of the condition indicator, considering: step-wise regression analysis, analysis of variance (ANOVA), t-Test, analysis of residuals.

8. Qualitative Condition Analysis: This analysis was performed to determine the qualitative scale based on the qualitative evaluations of the expert panel for networks evaluated.

9. Validation: To validate the models obtained in the regressions, the UPCI obtained by the models were compared with the UPCI_{OBS} obtained by the expert panel evaluations.
10. Cross-Validation: A statistical comparison between Manual and Automated UPCI was performed for each type of pavement to analyze whether the manual equations could be used with automated data collection and vice versa.
11. Recommendation for UPCI use and Urban Pavement Evaluation Methodology: Finally, recommendations were made for the use of UPCI equations and the Evaluation Methodology of the tools developed in this part of the study.

4.4 Experimental Design for the Calibration and Validation of Performance Models

4.4.1 Method Selection

To select the method most suitable for calibrating the performance models for urban networks, it is important to mention that no historical data for urban pavement conditions are available to be analyzed in this research. Therefore, all of the data to develop the performance models was collected during the research time frame, and this fact gave the limitation of a short period of time for pavement analysis of approximately 2 and a half years.

Given this limitation and based on the literature review presented in section 2.3.1, the method selected to use in this research was the Markov modeling method. This method allows the representation of non-linear models with a small amount of database.

4.4.2 Variables and Factorial Design Definition

The dependent variable is the UPCI measured at a specific moment in time. These evaluations were performed in sections that were not maintained between the evaluations.

The independent variables are distresses, pavement type, hierarchy, climate and time.

The factorial design for the development of the UPCI is presented in Table 4-5. This factorial has six factors: Distresses with different level for each pavement type, Pavement Type with two levels, hierarchy with five levels, climate with three levels, time with three levels, and UPCI calculated with nine levels.

The inference space of the factors describing the factorial design is the following:

- Distresses: Included in equations 1 to 4 of the section 6.3 for each type of pavement.
- Type of pavement: Two types of pavement were considered in this research, asphalt and concrete pavements. Interlocking pavements were not considered for performance models development due to UPCI equations were not satisfactorily validated and the number of samples found in the network is not representative.
- Hierarchy: This variable included the combined effect of correlated factors, such as functional classification of urban streets, traffic loads and levels and structure (the material and strength). Five different hierarchies are included according to five functional

classifications—express, trunk, collector, service and, local and passages—with their particular traffic and structure. The functional classification was selected to use due to the standard design for urban pavements is based on this classification.

Table 4-5. Complete Factorial Design to Develop Performance Models

Concrete											
Asphalt											
	Climate		Dry			Mediterranean			Humid		
	UPCI		1 - 2	…	9 - 10	1 - 2	…	9 - 10	1 - 2	…	9 - 10
Time 1,2,3	Hierarchy	Express	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3
		Trunk	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3
		Collector	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3
		Service	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3
		Local	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3	UPCI 1,2,3

- Climate: Three types of climates are included: dry, Mediterranean and humid. Table 4-6 presents the characteristics of each type of climate based on humidity data from other projects that were developed in Chile (Chamorro 2012; MOP 2007) and temperature data obtained from climate stations in Chilean cities (DGAC&DMC 2011). The considered climates are representative of different regions in Chile—north (Antofagasta), center (Santiago) and south (Puerto Montt)—respectively.

- Time: Three evaluations overtime are considered for all cases separated in 1 year and 9 months, respectively. In the case of mediterranean climate there are two additional evaluations at different times carried out collection data of part of the network.

- UPCI: Nine levels of UPCI are considered baseo on ranges of UPCI value =1, from 1 to 10.

Table 4-6. Climates Definition

Factors / **Climate**		**Dry**	**Mediterranean**	**Humid**
Precipitation (MOP, 2007; Chamorro, 2012)	Rainy Season	< 4 months	4 – 8 months	> 8 months
	Monthly Max. Precipitation	< 50 mm	50 – 400 mm	> 400 mm
	Annual Mean Monthly Precipitation	< 20 mm	20 – 200 mm	> 200 mm
Temperature (DGAC & DMC,2011)	Annual Mean Monthly	> 12 °C	8 – 12 °C	< 8 °C
Selected City		Antofagasta	Santiago	Puerto Montt

4.4.3 Sample Size estimation

Homogeneous sections are defined as segments of pavement in one street with the same conditions. Two sample units were set to be collected per homogeneous section of pavement, and two more sample units as replicates in other sections for each factorial cell.

The reason to evaluate replicate sample units in other sections was defined to analyze the variability of the performance within the parameters that are defined in this research as equivalent (hierarchies and UPCI).

If all groups are found in the field, a total of 135 sample units complete the factorial per pavement type and climate to be balanced. However, this factorial design is unbalanced due to the aim is to collect the real distribution of distresses and UPCI within the networks evaluated.

4.4.4 Methodology for Development of Performance Models

The methodology followed for the development of performance models is presented in Figure 4-3.

This methodology includes the stages followed to perform the data collection and analysis for the development of the performance models:

1. Experimental Design to Develop Performance Models: An experiment for the development of the performance models was defined, including the selection of the condition evaluation methodology; the definition of the dependent and independent variables, the scenarios and factorial design, and the probabilistic modeling method for the calibration of performance curves was selected.

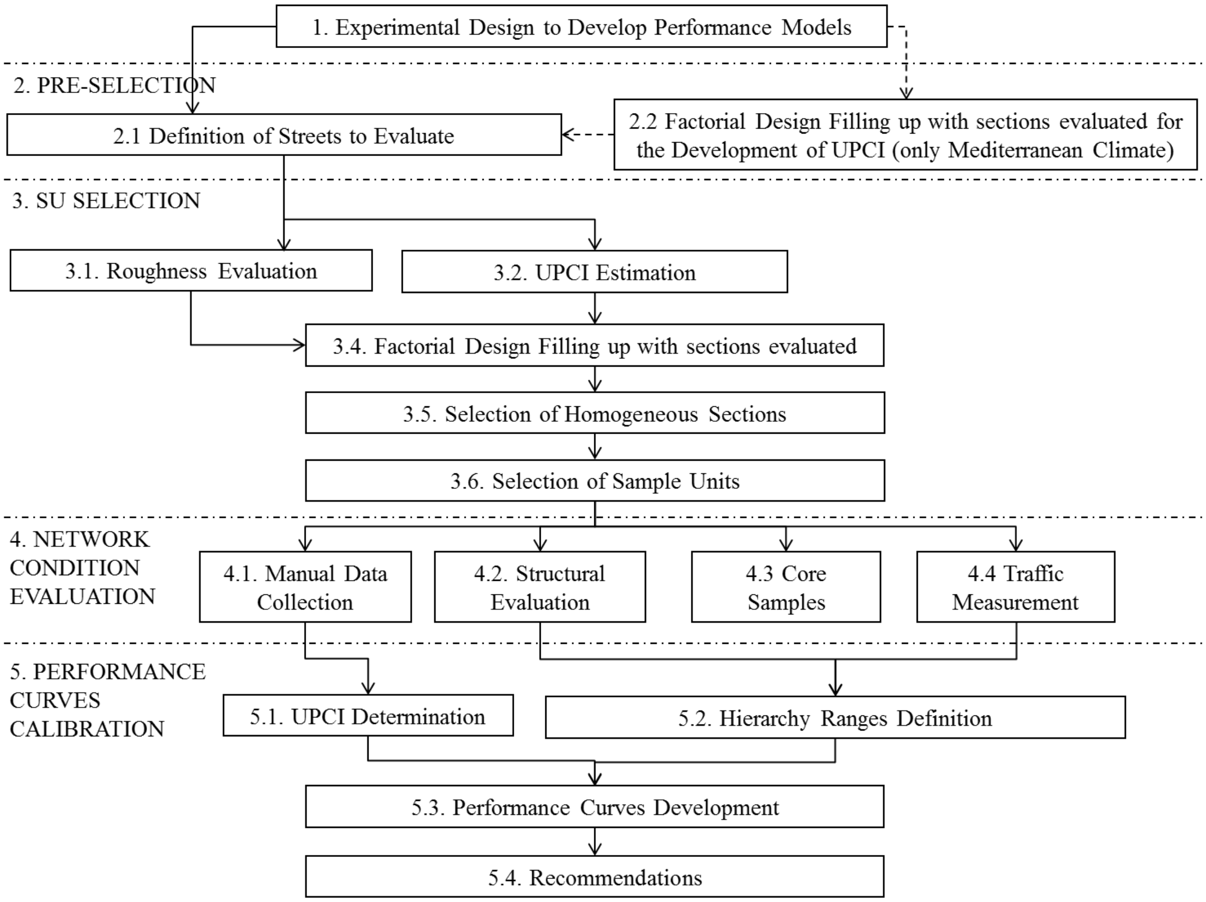


Figure 4-3. Data Collection and Analysis Methodology for the Development of Performance Models

2. Pre-selection: In this stage, the streets to evaluate were selected. This selection was part of the office work before the field evaluation and included the following steps:
    2.1. Definition of Streets to Evaluate: This selection was done based on the functional classification per type of pavement, information that was provided by the local agencies.

    2.2. Factorial Design Filling up with Sections Evaluated for the Development of UPCI: The sections evaluated in the Development of the UPCI (only Mediterranean Climate) were considered for this task. These sections were evaluated at four different times during the research.

3. Sample Unit (SU) Selection: In this stage, the selection of the sample units to be evaluated was performed, including field and office work.
    3.1. <u>Roughness Evaluation</u>: These evaluations were performed with the equipment Roughometer III (RIII), which measures IRI directly. This task began with the analysis of the evaluations made with RIII compared with evaluations of the Laser Profiler to ensure that the measurements are equivalent.

3.2. UPCI Estimation: This task included a quick distress identification that was completed in parallel with the IRI evaluation, using the windshield sheet (Appendix A). Based on this identification, the UPCIs were estimated.

3.3. Factorial Design Filled up with Sections Evaluated: With the information of previous stages, the factorial design was filled up.

3.4. Selection of Homogeneous Sections: More homogeneous sections than necessary were selected to complete the factorial to have a backup in case that it was required after the manual evaluations.

3.5. Selection of Sample Units (SMs): Within the homogeneous sections, the sample units were selected for the posterior evaluations. The size of each SM was the same as the size used for the development of the UPCI.

4. Network Condition Evaluations: This stage consists of evaluations of SU in the field:

4.1.: Manual data collection: It was performed with the distress evaluation guidelines developed in previous stage of the research. Use of manual instead of automated data collection in this task of the research was selected to optimize the financial resources.

4.2. Structural Evaluation: Falling Weight Deflectometer (FWD) was used to evaluate the structure.

4.3. Core samples: Samples of the sections were took to know the thickness and type of layers that conformed the structures.

4.4. Traffic Measurement: Traffic counts of 15 min in peak and non-peak hours were performed.

5. Pavement Curves Calibration

5.1. UPCI Determination: With the manual data collected and the IRI, UPCIs were determined with the equations defined in the previous stage of the research.

5.2. Hierarchy Definition: Based on the structural and traffic evaluation, the ranges for each hierarchy will be defined.

5.3. Performance Curve Development: First, the probability transition matrices (PTMs) were defined for each scenario considered in the factorial included in the experiment design. Second, Monte Carlo simulations were performed considering a life cycle of 20 years for asphalt pavements and 25 years for concrete pavements. Last, the performance models were developed for each scenario with 75% of the data collected. This was an iterative process until the final model was completed.

5.4. Recommendations: Finally, recommendations about the use and future calibration of the curves developed were done. The final models were analyzed and their scope and limitations were considered.

4.5 Experimental Design for Recommendation of Maintenance Standards

The objective of this experiment is to frame the analysis of treatment effects in the UPCI order to recommend the maintenance standards for urban pavements.

4.5.1 Variables and Factorial Design Definition

The dependent variables are the UPCI before and after the P&M&R activities. Distress evaluations were performed before and after P&M&R activities to calculate the UPCI in each case. As the treatment available in the field to evaluate during the project time frame are few of a long list of treatment available in the state-of-the-art, historical data from the state-of-the-art and the-practice was collected and analyzed to complete the factorial design in the case of P&M&R activities that were not implemented during the research frame time in the network evaluated.

The independent variables in this case are the P&M&R activities. The definition of the P&M&R activities to be considered in the research were carried out as part of the study, based on the review of the state-of-the-art-and the practice of suitable technologies for urban pavements.

In Table 4-7 and Table 4-8, the factorial designs that will be used for data collection to study the effects of different P&M&R treatments in the pavements considered in this research are shown. The treatments already considered in the tables are the treatments that local agencies apply to maintain the urban pavements in Chile. Other treatments are considered based on the literature review and study of projects developed in other places.

Table 4-7. Factorial Design for P&M&R Effects on Asphalt Pavements

P&M&R Activities	**Asphalt**	
Crack Sealing	UPCI Before	UPCI After
Asphalt Overlay	UPCI Before	UPCI After
Pothole Patching	UPCI Before	UPCI After
Reconstruction	UPCI Before	UPCI After
Other Treatments	UPCI Before	UPCI After
⋮	⋮	⋮

Table 4-8. Factorial Design for P&M&R Effects on Concrete Pavements

P&M&R Activities	**Concrete**	
Crack Sealing	UPCI Before	UPCI After
Joint Sealing	UPCI Before	UPCI After
Slab replacement	UPCI Before	UPCI After
Reconstruction	UPCI Before	UPCI After
Other Treatments	UPCI Before	UPCI After
⋮	⋮	⋮

4.5.2 Methodology for the study of P&M&R Treatment Effects on the UPCI

The methodology defined for the study of the effects of the P&M&R treatments on the UPCI is shown in Figure 4-4.

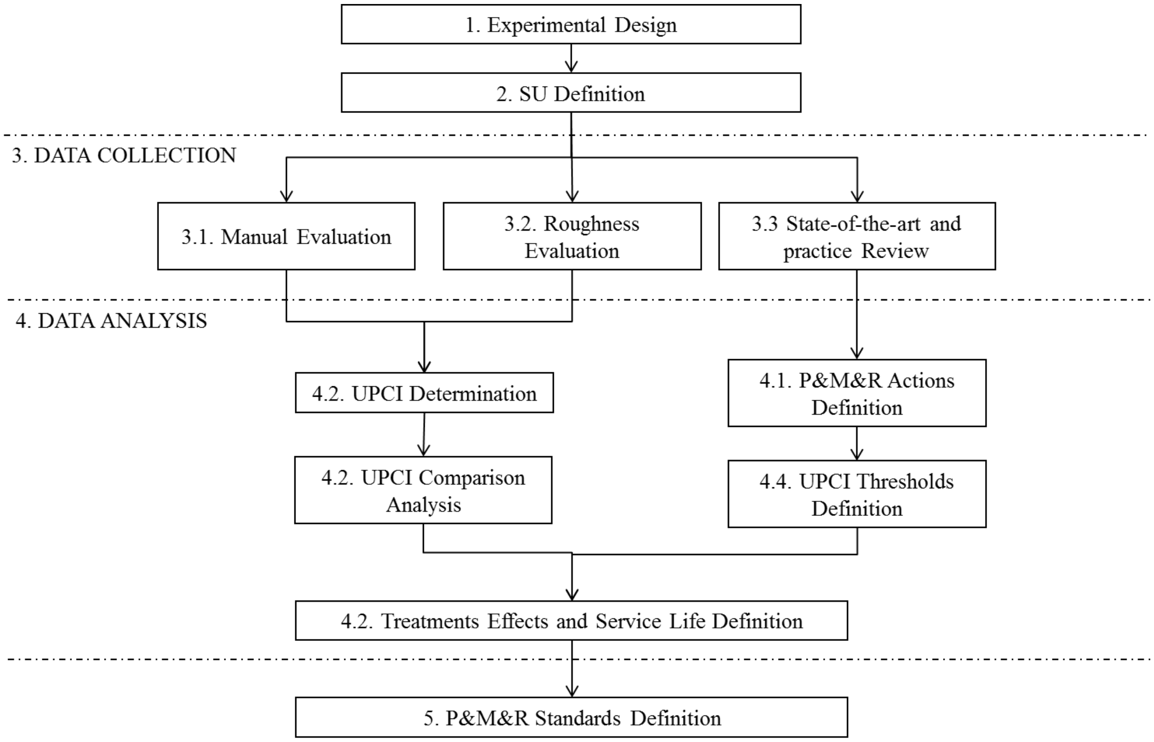


Figure 4-4. Methodology for P&M&R Standards Definition

The methodology includes the stages followed to complete the data collection and analysis for this part of the study:

1. Experimental Design: This task defines the variables included in the analysis and the steps followed for the data collection and analysis for the study of P&M&R treatment effects.
2. SU Definition: The SU was defined based on the information given by the local agencies about the section to be maintained during the period of the research. The size of each SU was the same for the development of the UPCI and performance models.
3. Data Collection:
    - 3.1. Manual Evaluation: It was performed with the same procedure defined in the Development of UPCI.
    - 3.2. Roughness Evaluation: These evaluations were performed with the equipment Roughometer III (RIII).
    - 3.3. State-of-the-art and practice Review: The information about P&M&R treatments performed in from the state-of-the-art and practice was collected.
4. Data Analysis:
    - 4.1. P&M&R Actions Definition: Actions recommended for urban pavement are presented.

   4.2. UPCI Determination: With the manual data collected and the IRI, the UPCI was determined with the equations 1 to 4 defined in section 6.3.
   4.3. UPCI Comparison Analysis: The enhancement of the UPCI by each P&M&R treatment was determined.
   4.4. UPCI Thresholds Definition: Were calculated though the analysis of combination of distresses triggering the P&M&R actions
   4.5. Treatments Effects and Service Life Definition: Were defined based on the information analyzed from field evaluations and the state-of-art-and-the practice.
5. P&M&R Standards Definition: Suitable standards for urban pavements are recommended based on the analysis of the information analyzed.

4.6 Chapter Summary

Three experimental designs were carried out for the development of the methodologies included in this thesis research. The reliability of the tools developed in this research relied on the consistency of the experimental designs presented in this chapter.

Data collection and analysis were conducted based on the variables, factorial designs and methodologies defined in these experimental designs.

Five data collection campaigns for distress and condition evaluations as well as three data collection campaigns for FWD evaluation, core sampling and traffic counts are included in these experimental designs for the development of the tools compromised in the research.

Chapter 5

Data Collection and Processing

In this Chapter are presented the methodologies followed to collect the data in the field and then process them. In addition, a summary of the data collected is presented.

5.1 Development of Distress Evaluation Guidelines

Distress evaluation guidelines were developed for manual and automated evaluation of urban pavements. In a first stage, a broad universe of distresses was considered for each type of pavement based on an extensive review of pavement evaluation protocols (FHWA 2003b; MINVU 1999; MOP 2010; MTO 1989). In a second stage, distresses were filtered based on field observations through windshield evaluations and a review of the current state-of-the-practice of urban pavement management.

The guidelines consider three severity levels, when the magnitude of distresses is not directly related to the severity of the distress. This is the case of cracking, patch deterioration and joint damage. In all other cases, severity was associated to the magnitude of the distress (FHWA 2003b; MOP 2010). Distress severity, magnitude and extent were collected in terms of objective measures as presented in Table 4-1 to Table 4-3.

Automated data collection was performed to evaluate the following distresses:

- Surface distresses: Evaluated in asphalt and concrete pavements through automated digital images with the equipment Pave Inspect Uni Survey. Data analysis was analyzed with semi-automated analysis software (APSA 2004; Chamorro 2004).
- Roughness (IRI): Evaluated in concrete and asphalt pavements, part of the sections with a laser profiler and all the sections with Roughometer III (RIII). The data was collected every 10 m with both equipment. The evaluations with the laser profiler were performed following the ASTM E1926 - 08 (ASTM 2003b).
- Rutting: Evaluated in asphalt pavement with a laser profiler, with data collected every 10 m.

5.2 Validation of Distress Evaluation Guidelines

The repeatability was tested to evaluate the variability of the evaluations performed under the same conditions. In both types of evaluations, manual and automated, the repeatability was checked for evaluators and equipment, respectively.

t-Tests for comparison of means was used for this analysis, with 30 segments evaluated twice by the same rater. The second set of data was undertook a week after the first set. The test was performed for each type of distress, level of severity and type of pavement for manual and automated data collection.

The hypothesis test done was the following:

- Null hypothesis, H0: $\mu_1 = \mu_2$, where μ_1 y μ_2 are the means of each group of evaluations
- Alternative hypothesis, H1: $\mu 1 \neq \mu 2$
- The null hypothesis is rejected when the p value < 0.05. In this case, the difference between means is significant.

In the manual evaluations, statistically equivalent replicates were obtained with a 95% confidence level for all distresses for both pavements, except for the following:

- Shoving, bleeding and polished aggregates for asphalt pavements
- Scaling and polished aggregates for concrete pavements

The reason of poor repeatability of these distresses is that they were observed with low frequency in the evaluated sections so the rater did not have much experience to assess them. Likewise, these distresses were not statistically significant within the regression analysis as it can be note in section **¡Error! No se encuentra el origen de la referencia.**.

In the automated evaluations, statistically equivalent replicates were obtained with a 95% confidence level for surface distresses, roughness and rutting.

The reproducibility analysis was carried out to evaluate the variability between different evaluators for manual data collection. For automatic data collection, the reproducibility was assumed from a study previously performed by the company that makes the evaluations.

ANOVA Test for Random Block Design was used for this analysis, considering blocks for the evaluated segments and treatment for the raters. Analysis of variance was applied for each of the compared distress measures to determine if the differences between measured distresses were statistically significant. For this analysis, 20 to 30 segments were evaluated by three and four raters. This test was performed for each type of distress, severity level, and type of pavement.

Although the raters received training to collect distress data, only some distresses present good reproducibility with a 95% confidence level. This shows the importance of having experienced raters, good training and the need of clear guidelines to perform the data collection. For the evaluations of the sections in this research, evaluators with good reproducibility performed the data collection.

In the Appendix B is presented the Evaluations Guidelines including the distresses considered in the UPCI equations presented in section **¡Error! No se encuentra el origen de la referencia.**.

5.3 Field Data Processing

Data was collected in each sample unit considering the distresses aforementioned. In addition the following inventory and reference data was collected: name of street; type of pavement, width, length and traffic direction of the lane, start and end reference, geographical reference (collected with GPS).

The distresses were converted to a percentage of evaluated area for statistical analysis, except for the following distresses, which were used in their original measuring units:

- Rutting for asphalt pavements (mm)
- Faulting for concrete pavements (mm)

- Skid resistance for interlocking pavements (BPN: British Pendulum Number)
- Manholes and catchbasins for all types of pavements (units)
- Roughness (m/Km)

An area of 0.50m deteriorated in both sides of the crack was considered for all types of cracking. Therefore, 1 m^2 of deteriorated area was considered for each meter of cracking.

The representative value for IRI and rutting was the average between the measurements in both wheel paths.

The distresses with three levels of severity were weighted based on their severities to include in the regression analysis. The weights are 0.5, 1 and 2 for low, moderate and high severities.

An outlier analysis was performed using Chebyshev's theorem. This method allows for detection of multiple outliers, assumes that the data are independent measurements and, that a relatively small percentage of outliers are contained in the data. Chebyshev's inequality gives a bound of what percentage of the data falls outside of k standard deviations from the mean. In this research 3 standard deviations were used for the calculation. Data values that were not within the range of the upper and lower limits were considered as outliers. Outliers were detected and most of them correspond to erroneous data. All outliers were removed from the data to continue the analysis.

Once the data were processed and outliers removed, 75% of the values were separated for the calibration and 25% for the validation on both cases, for UPCI and performance models.

5.4 Data Collected for Calibration and Validation of UPCI

5.4.1 Network Evaluated

The network selected for this part of the research comprises the pavements of three municipalities within Santiago, Chile, with a total extension of 810 Km (MINVU 2008b). The streets within the network present diverse functional classifications, geometric designs, traffic types and volumes, pavement structures, foundations and seasonal climate conditions. Three institutions are responsible for the management of the selected network, namely: municipalities, the regional government and the Ministry of Housing and Urbanism.

The network presents pavements belonging to six functional classes according to the Ministry of Housing and Urbanism classification: express, trunk, collector, service, local and passages. The first two categories comprise the primary network, the third and fourth to secondary network, and the last two the local network. Traffic volumes can range from 600 to more than 4000 veh/hr for primary streets, and less than 600 veh/hr for local streets (MINVU 2008a). Structures were designed based on traffic volumes, equivalent axles and types of soils following the structural design for urban pavements defined by the Ministry (MINVU 2009).

The field evaluation with manual and automated data was performed during June 2012. The data was collected with the guidelines presented in the Appendix B. The data used in the regression analysis is presented in Appendix D. Additionally, validation of the UPCI equations was performed with the data collected for performance models.

5.4.2 Experts Panel Evaluations Analysis

The $UPCI_{OBS}$ of the selected sections was assessed by an expert panel formed by experienced professionals of academia, private and public sectors. The panel rated each sample unit in terms of the combined effect of distress types and severities observed in the field in a scale that ranged from 1 to 10, where 1 was the worse condition and 10 the best.

The experts participated to a training session in order to have the same criteria when evaluating the sections. The main criteria for evaluating the section was the type of maintenance treatment required for improving the sections to the best condition.

A paired sample t-Test for mean comparison was performed to analyze the equivalence of $UPCI_{OBS}$ between raters. For all types of pavements it was observed that three experts were statistically equivalent. The statistical analysis carried out is presented in Appendix C.

The average of $UPCI_{OBS}$ between the equivalent raters for each sample unit was considered in the regression analysis. The final values used for the regression analyses are presented in Appendix D.

5.4.3 Summary of Data Collected

Approximately 60 asphalt, 90 concrete, and 50 interlocking sample units remained for the calibration and validation of the UPCI after the outliers elimination. The amount of sample sections demonstrated to be sufficient to obtain a reliable statistical analysis, considering the sample size estimation of scenarios presented in 4.3.2. This data processed, used for the regression analysis is presented in Appendix D. Table 5-1 presents a summary of the data collected for each type of pavement.

Table 5-1. Quantity of sections evaluated

Sections Evaluated (Number)			
Range	Asphalt Pavements	Concrete Pavements	Interlocking Pavements
10 - 9	3	8	0
9 - 8	5	14	1
8 - 7	3	3	2
7 - 6	11	23	11
6 - 5	13	17	18
5 - 4	11	13	11
4 - 3	3	6	6
3 - 2	4	7	0
2 - 1	1	0	0

Additionally, Table 5-2 and Table 5-4 show how the factorial design for each type of pavement was filled with the data collected and used in the regression analysis.

Table 5-2. UPCI Factorial Matrix Filled for Asphalt Pavement

						Fatigue Cracking			
						No		Yes	
						Transversal & Reflection Cracking			
						No	Yes	No	Yes
Deteriorated Patch	No	Potholes	No	Rutting	No	3	6		3
					Yes	2	6	4	8
			Yes		No	1	▨	▨	▨
					Yes	▨	▨	▨	1
	Yes		No		No	▨	1	1	1
					Yes	▨	▨	2	12
			Yes		No	▨	▨	▨	▨
					Yes	1	▨	1	1

▨ Combinations Not found

Table 5-3. UPCI Factorial Matrix Filled for Concrete Pavement

								Corner and Oblique Breaks			
								No		Yes	
								Longitudinal Cracking			
								No	Yes	No	Yes
Transversal Cracking	No	Deteriorated Patched	No	Faulting	No	Seal Damage	No	2	▨	▨	▨
							Yes	2	▨	▨	▨
					Yes		No	1	1	▨	▨
							Yes	13	2	1	1
			Yes		No		No	▨	▨	▨	▨
							Yes	▨	▨	▨	▨
					Yes		No	▨	▨	▨	▨
							Yes	▨	▨	▨	▨
	Yes		No		No		No	▨	▨	▨	▨
							Yes	2	2	1	▨
					Yes		No	▨	1	▨	▨
							Yes	9	13	1	17
			Yes		No		No	▨	▨	▨	▨
							Yes	▨	▨	1	▨
					Yes		No	▨	▨	▨	▨
							Yes	5	5	1	10

▨ Combinations Not found

Table 5-4. UPCI Factorial Matrix Filled for Interlocking Pavement

				Cracking and Seal Damage	
				No	**Yes**
Deteriorated Patch	**No**	**Potholes**	**No**	4	8
			Yes	▨	1
	Yes		**No**	4	29
			Yes	▨	3

▨ No se enontraron secciones

5.4.4 Power Analysis of Data Collected

The estimation of the power of the data processed for the regression analysis was performed to analyze how the sample size used for the regression analysis ensure the precision and accuracy of the regression coefficients.

In this analysis the a Post hoc method was carried out, determining the power (1- β) of the sample size with the number of samples, a probability error (α) and an effect size (f). The method implemented by (Erdfelder E. et al. 1996) in the software GPower was applied. This method assumes the correlation coefficient R^2 improves with the addition of predictors (Cohen J. 1988; Echaveguren T. 2008).

The values assumed for the power analysis were:

- Probability error (α) = 0.05
- Effect size (f) = 0.15 medium effect size by convention (Cohen J. 1988; Echaveguren T. 2008)
- Numerators and Predictors = are the same number for type of pavement and are presented in Table 5-55.

As a result of this analysis, the power of the sample size for each pavement was obtained as is presented in Table 5-55. The power resulted for the three cases are low, considering a good power number above 0.7 (Cohen J. 1988; Echaveguren T. 2008). Further analysis is needed to perform in order to ensure the power of the sample of UPCI models.

Table 5-5. Results of Power Analysis for Multilinear Regression

Pavement Type	Asphalt	Concrete	Interlocking
Predictors	5	6	3
Sample Size for Calibration	38	61	34
Power	0.35	0.54	0.40

5.5 Data Collection for Performance Models Calibration and Validation, and Maintenance Effect Definition

5.5.1 Network Evaluated

The selection of the network for this development was carried out based on climate conditions and strategic location of the cities. This selection was decided with authorities of the Ministry of Housing and Urbanism, who will be one of the main users of the tools developed in this research.

Pavement networks from three Chilean cities were selected, representing each climate included in the scenarios of the factorial design. The cities locations are presented in Figure 5-1, and their main characteristics are the following:

- Mediterranean Climate: Santiago, with a population of 5.631.839 hab and area of 69.781 Ha
- Dry Climate: Antofagasta, with a population of 285.255 and area of hab 2.686 Ha
- Humid Climate: Puerto Montt, with a population of: 175.140 and area of hab 2.343 Ha.

Five evaluations of distresses were carried out to obtain the UPCI at different times. The evaluations were performed during June 2012, January 2013, January 2014, October 2014, and December 2014. The six-month period between June 2012 and January 2013 was considered to analyze the effect of the winter season on the evolution of the UPCI. This evaluation was performed only for Mediterranean climate in Santiago. The evaluations in December 2014 were also performed only in Santiago for using in the validation process. All the unit samples evaluated considered for this part of the research where not maintained between evaluations.

The total sample units evaluated per climate region are the following:

- Mediterranean Climate (Santiago): 200 asphalt sample units and 150 concrete sample units.
- Dry Climate (Antofagasta): 165 asphalt sample units and 10 concrete sample units.
- Humid Climate (Puerto Montt): 35 asphalt sample units and 100 concrete sample units.
- The number of sample sections for obtaining a reliable statistical analysis was sufficient for asphalt and concrete for Mediterranean climate, asphalt for dry climate, and concrete for humid climate.
- Data were collected in each sample unit following the Distress Evaluation Guidelines presented in Appendix B, considering the distresses included in equations 1 and 4 of section 6.3. The data collected for these conditions are presented in Appendix E.
- Additionally, three field evaluation campaigns were performed to collect data from the structure with Falling Weight Deflectometer and core sampling, and from traffic with traffic counts.

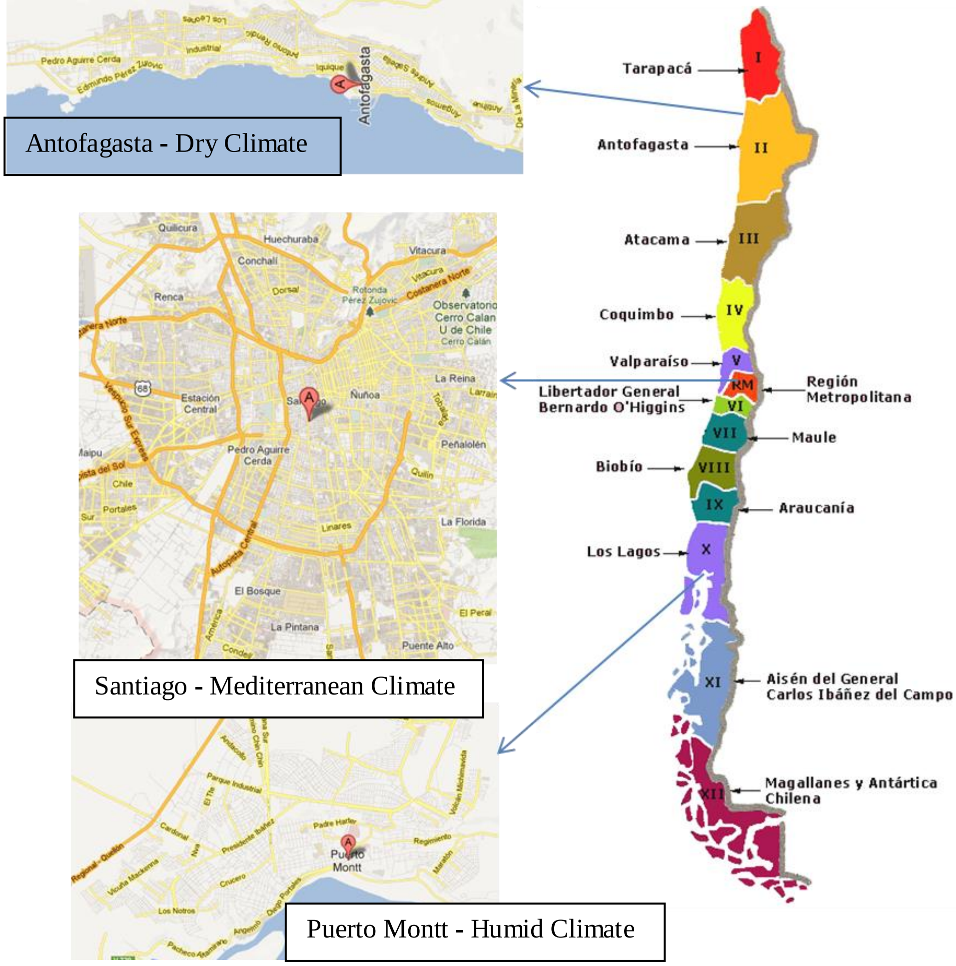


Figure 5-1 Networks selected for Performance Models Development, Maintenance Effect Definition and Validations

5.5.2 Summary of Data Collected

The data processed and used for calibration of performance models for each scenario considered in Chapter 7 is presented in Appendix E.

A summary of data collected for calibration and validation of performance models per pavement type and climate is presented in Table 5-6 in terms of quantity of sample units and length of the network represented by those sections.

Table 5-6. Summary of Data Collected for Performance Models

Climate	Asphalt Pavements		Concrete Pavements	
	Sample units	Length Represented (Km)	Sample units	Length Represented (Km)
Dry	94	28.22	-	-
Mediterranean	93	56.19	150	85.65
Humid	-	-	49	11.87

Additionally, Table 5-7 and Table 5-8 show how the factorial matrices for each type of pavement, climate and hierarchy were filled with the data collected. These sample units were used in the calibration and validation of performance models.

Only a few sample units were collected in the cases of asphalt pavement in humid climate and concrete pavements in dry climate. For this reason the matrices do not present data for these conditions. In Chapter 7 is presented the analysis performed for these cases.

5.6 Chapter Summary

Evaluation guidelines were developed and satisfactory calibrated thought repeatability analysis of the evaluations. Further analysis is needed to validate the reproducibility of the guidelines. Training of the raters is fundamental to improve the reproducibility of the guidelines.

Data collection is presented including the networks evaluated with their main characteristics, field data processing, summary of data collected in the evaluation campaigns and factorial matrices filled.

Table 5-7. Factorial Matrix Filled for Asphalt Pavement

			Sample Sections of Asphalt Pavement																	
	Climate		Dry									Mediterranean								
	UPCI		10 - 9	8.9 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	10 - 9	8.9 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1
Time 1	Hierarchy	Express	1	1	0	0	0	0	0	1	1	9	1	0	1	2	0	0	0	0
		Trunk	5	2	0	1	0	0	0	2	2	10	2	2	1	0	0	1	1	0
		Collector	11	4	1	2	0	0	0	0	1	5	2	1	1	1	0	0	0	0
		Service	4	2	0	0	0	0	0	0	1	9	4	2	0	1	2	2	0	0
		Local	12	1	0	1	0	0	1	0	0	4	2	5	3	0	2	2	0	0
Time 2	Hierarchy	Express	3	1	1	0	0	0	0	1	1	8	3	0	1	2	0	0	0	1
		Trunk	9	3	2	0	4	1	5	4	3	10	3	2	0	2	0	0	1	2
		Collector	12	3	5	3	0	1	2	0	1	5	1	1	2	2	0	0	0	1
		Service	4	2	1	0	0	0	0	1	2	3	4	5	3	2	2	3	1	1
		Local	11	2	0	2	2	0	1	1	0	1	3	6	3	2	3	1	2	1
Time 3	Hierarchy	Express	3	0	2	0	0	0	0	1	1	6	3	2	0	1	1	1	0	1
		Trunk	4	3	1	1	1	2	5	4	3	9	3	1	2	1	1	0	0	2
		Collector	7	3	2	4	1	1	0	2	0	4	2	0	2	3	0	0	0	1
		Service	3	0	1	1	0	0	0	0	1	2	4	4	3	3	2	1	2	1
		Local	4	1	2	0	0	1	0	2	0	1	1	7	2	2	3	1	1	2
▨	Sections not found																			

Table 5-8. Factorial Matrix Filled for Concrete Pavement

			Sample Sections of Concrete Pavement																	
	Climate		Mediterranean									Humid								
	UPCI		10 - 9	8.9 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1	10 - 9	8.9 - 8	7.9 - 7	6.9 - 6	5.9 - 5	4.9 - 4	3.9 - 3	2.9 - 2	1.9 - 1
Time 1	Hierarchy	Express	5	3	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
		Trunk	4	10	7	5	2	2	0	0	0	0	1	0	0	0	0	0	1	1
		Collector	4	7	6	5	9	5	2	0	0	4	0	1	0	1	0	0	0	0
		Service	1	5	7	3	3	1	0	0	0	0	1	2	1	4	1	0	0	0
		Local	2	8	7	4	8	3	1	6	0	0	0	0	0	0	0	0	0	0
Time 2	Hierarchy	Express	5	2	3	4	1	1	0	0	0	0	0	0	0	0	0	0	0	0
		Trunk	1	8	8	6	5	2	1	0	0	1	3	1	2	1	1	1	1	1
		Collector	2	5	5	6	2	19	2	1	0	5	2	2	1	0	1	1	0	0
		Service	1	5	5	4	4	3	0	0	0	0	3	1	2	4	3	2	1	0
		Local	2	5	7	4	8	3	4	4	2	0	1	1	3	2	2	0	0	0
Time 3	Hierarchy	Express	1	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0
		Trunk	1	1	6	4	4	3	1	0	0	0	3	0	3	1	0	1	1	1
		Collector	0	4	4	5	2	12	3	0	0	2	3	1	1	0	0	2	0	1
		Service	0	3	4	4	3	1	0	0	0	0	2	1	2	0	3	3	1	0
		Local	0	3	2	3	9	2	1	1	1	0	0	1	3	3	2	0	0	0
▨	Sections not found																			

Chapter 6

Calibration and Validation of Urban Pavement Condition Index

This chapter presents the Calibration and Validation of the Urban Pavement Condition Index for asphalt and concrete pavements considering manual and automatic evaluations.

The results presented in this chapter was presented at the 93th Transportation Research Board annual meeting, published in the proceeding of the conference and later published in the Transportation Research Record (Osorio et al. 2014).

6.1 UPCI Calibration

Multiple linear regression analyses were performed to calibrate UPCI equations, between the $UPCI_{OBS}$ and the distresses evaluated in field. The analyses were carried out separately for asphalt and concrete pavements, and for manual and automated data, giving a total of four UPCI equations. Lineal regression was chosen following the example of other indices and presents good results. For this reason other types of relations were not proof.

The 75% of the data collected was used for the calibration and the 25% for the validation of the index, for asphalt pavements. In the case of concrete pavements, 67% of the data was used for calibration and 33% for validation.

The methodology of the regression analysis is presented in Figure 6-1. ANOVA analyses were applied to evaluate the overall significance of regressions. Two-tailed t-Tests were performed to analyze the significance of independent variables considered in the analysis. Mean Square Error (MSE) was estimated as part of ANOVA analyses and used to determine the F and t values. A 95% confidence level was used for both analyses. Finally, residuals were analyzed to evaluate if the models fit well the data. All the analyses were carried out with the software IBM SPSS Statistics 20. The results of regression analysis carried out are presented in Appendix F.

The results indicate that the overall significance of regressions was satisfactory for manual and automated data collected of asphalt pavements and manual data collected of concrete pavements. Overall significance is satisfactory when F statistic of each regression was higher than the critical F value.

Independent variables with positive coefficients or low significance in each regression were eliminated following a stepwise method. This method was carried out based on the p-value of F (probability of F) using 0.05 as probability to enter a variable and 0.10 as probability to remove a variable.

The outlier analyses were performed after generating the first regression using the Cook’s Distance method (Cook, R. D. 1979), which determines the influence points in multiple linear regressions. The points indicated by this analysis were studied considering technical criteria in order to decide the need of elimination. For example, if a section was indicated as an outlier in this analysis, the section characteristics, distresses types and quantity, and field observation were checked to decide if it was necessary to eliminate the outlier. This process was iterative in case of elimination of outliers, when regressions were developed without the eliminated sections.

The developed equations did not represent the maximum or minimum values of UPCI in cases where very good or very poor conditions were observed. It is assumed that it was because the raters were hesitant when evaluating section with extreme conditions (very good or very poor) (Chamorro et al. 2009a). In order to correct the residuals, the equations were adjusted with the factor of the maximum of UPCI=10 divided by the intercept of the regression, to obtained the final equations ($UPCI_{ADJ}$), following the Equation 1.

$$UPCI = 10 + \sum(Coef.\ x\ \%Distresses) \qquad (1)$$

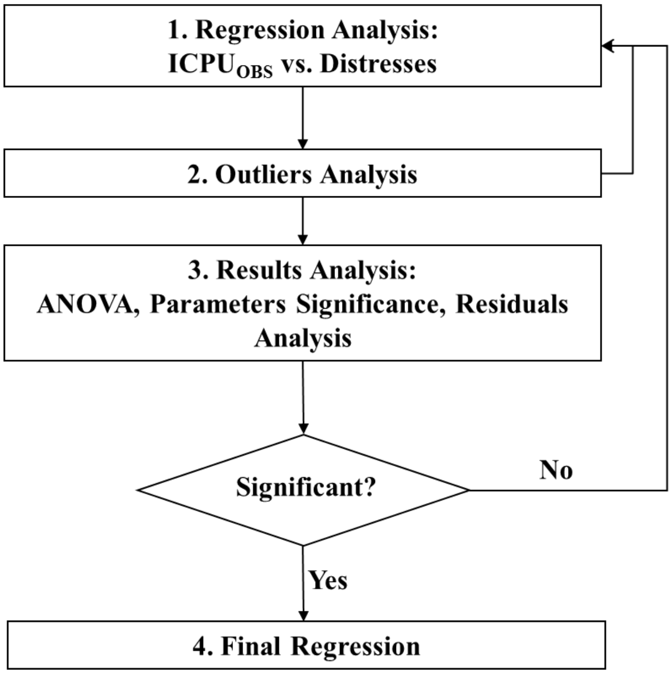


Figure 6-1. Regression Analysis Methodology

The following modifications to distresses were made to improve the coefficient of determination and the residuals observed in the regression analysis:

- For asphalt pavements, the effect of transverse and reflection cracking were summed in the equations as no statistical difference was observed when considering their effect in the overall condition of the pavements.
- For concrete pavements, the effect of corner and oblique breaks were summed in the equations. Also, the effect of seal damage and spalling of transverse and longitudinal joints were combined and renamed as joint damage. The level of spalling observed in a joint was considered as a criteria to rate distress severity.

Four final equations were obtained with good statistical results. In the case of asphalt pavement, for manual and automated data collection and for a combination of distresses collected manually with IRI, whereas in the case of concrete pavements, for manual data collection (Equations 1 to 4):

$$\textbf{Asphalt } \mathbf{UPCI_{MANUAL} = 10 - 0.038\,FC - 0.049\,TRC - 0.046\,DP - 0.059\,R - 0.237\,P} \tag{1}$$

$R^2 = 0.81$; $R^2_{ADJ} = 0.78$; $N = 38$; Std Error $= 0.79$

$F = 27.95 > F_{crit} = 2.51$

$$\textbf{Asphalt } \mathbf{UPCI_{AUTO} = 10 - 0.031\,FC - 0.040\,TRC - 0.028\,DP - 0.082\,R - 0.143\,IRI} \tag{2}$$

$R^2 = 0.94$; $R^2_{ADJ} = 0.93$; $N = 36$; Std Error $= 0.48$

$F = 94.54 > F_{crit} = 2.53$

$$\textbf{Asphalt } \mathbf{UPCI_{MANUAL+IRI} = 10 - 0.032\,FC - 0.046\,TRC - 0.041\,DP - 0.057\,R - 0.149\,IRI} \tag{3}$$

$R^2 = 0.85$; $R^2_{ADJ} = 0.83$; $N = 38$; Std Error $= 0.70$

$F = 37.14 > F_{crit} = 2.51$

Where:
FC: Fatigue cracking (%)
TRC: Sum of transversal and reflection cracking (%)
DP: Deteriorated Patch (%)
R: Rutting in mm, calculated as the average of rutting of segments in the sample unit
P: Potholes (%)
IRI: International Roughness Index in m/km, calculated as the average of roughness of segments in the sample unit

$$\textbf{Concrete } \mathbf{UPCI_{MANUAL} = 10 - 0.042\,LC - 0.025\,TC - 0.063\,DP - 0.263\,F - 0.038\,COB - 0.018\,JD} \tag{4}$$

$R^2 = 0.81$; $R^2_{ADJ} = 0.79$; $N = 38$; Std Error $= 1.09$

$F = 39.48 > Fcrit = 2.27$

Where:

LC: Longitudinal cracking (%)
TC: Transversal cracking (%)
DP: Deteriorated Patch (%)
F: Faulting in mm, calculated as the average of faulting of each slab in the sample unit
COB: Sum of corner and oblique breaks (%)
JD: Joint Damage in percentage of the total meters of joins existing in the sample unit

Following the data processing, the cracking and deteriorated patch were weighted based on their severities before ingress into the equations. The weights for severities are 0.5, 1 and 2 for low, moderate and severe severity.

6.2 Validation of Urban Pavement Condition Index

Validation was performed with remaining data not considered in the regression analysis. Statistical analyses considered two-tailed t-Tests for difference in means with a confidence level of 95%. Two different validations were carried out: an initial validation of each independent equation and a cross – validation to contrast manual and automated equations for each pavement type.

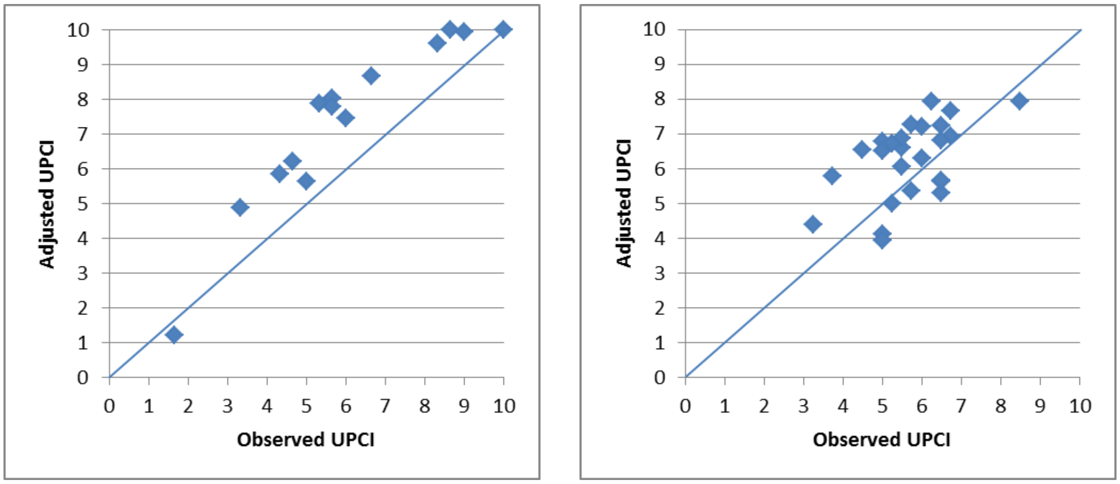
6.2.1 Validation of Manual and Automated Equations

In this validation the values observed in the field by the Expert Panel ($UPCI_{OBS}$) were compared with the calculated UPCI values obtained from distresses and adjusted equations ($UPCI_{ADJ}$).

For manual data collected, the validations of asphalt and concrete pavement equations were performed with 14 and 25 sections, respectively. The t values were the following:

- $t = -5.751 > t_{crit}$ (0.025,15)= -2.131 for asphalt pavements
- $t = -2.242 >, t_{crit}$ (0.025,29)= -2.045 for concrete pavements

Therefore, the equations were successfully validated, where no significant difference was observed between sample means, as presented in Figure 6-2. As it can be observed, in the case of asphalt pavements (a) the UPCI model delivers a little higher condition than the $UPCI_{OBS}$ but the difference is not statistically representative.



(a) (b)

Figure 6-2. Validation of $UPCI_{MANUAL}$ equation for asphalt (a) and concrete (b) pavements

Validation was performed with 15 sections for each type of pavement for automated data. The equations for both types of pavements were not successfully validated after adjusting the intercepts; however, the original equations were validated satisfactorily.

6.2.2 Cross – Validation between Manual and Automated Equations

The cross-validation consisted in the statistical comparison of results when using manual data in manual and automated equations, likewise, when using automated data with both equations. The t values resulting from the analysis were -4.813 and -5.877, both greater than t_{crit} (0.025,15) = -2.131. Therefore, the equations for asphalt pavements were cross-validated successfully as presented in Figure 6-3 and Figure 6-4. Is can be observed, the manual UPCI equation delivers values of condition a little higher than the automated equation but the difference is not statistically representative.

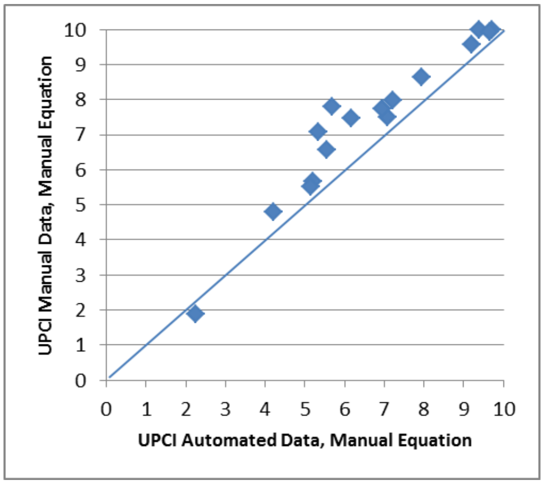


Figure 6-3. Validation of $UPCI_{Asphalt}$ using manual and automated data - Manual Equation

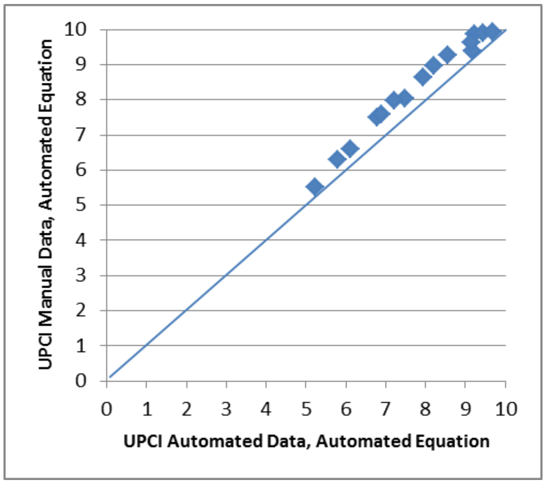


Figure 6-4. Validation of $UPCI_{Asphalt}$ using manual and automated data - Automated Equation

Both equations can be used with manual and automated data giving equivalent results. As the automated UPCI include the IRI, this equation is recommended only when IRI values are available. In other cases, when manual data or automated data without roughness measures is available, the Manual UPCI equation is recommended. This is supported by the fact that the manual equation includes potholes, which are not included in the automated equation. In addition, an equation combining manual collected distresses with IRI values was developed.

The adjusted equations for concrete pavements did not give satisfactory results for the cross-validation. The main reasons for this are:

- UPCI equation for automated data does not consider the same distresses included in the UPCI equation for manual data, causing that some distresses are not represented in the automated equation;
- Possible correlation between independent variables considered in the automated regression may be affecting the regressions, considering distresses and IRI values;
- Difference in the evaluation methodology between manual and automated data collection may be affecting the regressions. For example, faulting considered in manual evaluations is represented by the IRI value in automated evaluations, while manual evaluations consider faulting evaluations.

Considering the aforementioned reasons, it was concluded that UPCI equations for concrete pavements considering automated data require further analysis.

The adjusted equations for interlocking pavements were not validated successfully for any type of data collected. This may be explained by these reasons:

- Possible correlation between independent variables considered in the regression
- The expert panel present high variability in the UPCI observed evaluated in the field.

6.3 Analysis of UPCI Calibrated and Validated

The regressions values obtained had good coefficient of determinations. The detailed statistical analysis for each case is presented in Appendix F.

The statistic values are presented in Table 6-1 to Table 6-4. In every case, the t values of variables are higher than the t_{crit} presenting statistically significance with the exception of potholes for asphalts but this distress was kept in the UPCI model due to its importance in pavement behavior.

The coefficients of correlation are also presented, positive correlation means direct correlation and negative inverse correlation. Between the variables considered on these equations the coefficients are not high showing weak correlation, with the exception of IRI in the Equation 3, which shows strong correlation with rutting and also moderate correlation with fatigue cracking. These are logical results considering that many distresses are usually reflected in IRI values.

Table 6-1. Statistics Values for Equation 1

Variables	t (t_{crit} = -2.037)	Correlation coefficients				
		FC	TRC	DP	R	P
FC	-7.402	1.000				
TRC	-5.116	-0.249	1.000			
DP	-3.139	0.336	-0.148	1.000		
R	-2.162	0.066	0.176	0.156	1.000	
P	-0.499	0.475	0.071	0.120	0.019	1.000

Table 6-2. Statistics Values for Equation 2

Variables	t (t_{crit} = -2.042)	Correlation coefficients				
		FC	TRC	DP	R	IRI
FC	-10.696	1.000				
TRC	-7.227	0.344	1.000			
DP	-4.06	0.103	0.032	1.000		
R	-6.104	-0.555	-0.225	-0.058	1.000	
IRI	-4.381	-0.285	0.076	-0.123	-0.125	1.000

Table 6-3. . Statistics Values for Equation 3

Variables	t (t_{crit} = -2.037)	Correlation coefficients				
		FC	TRC	DP	R	IRI
FC	-6.740	1.000				
TRC	-5.588	-0.249	1.000			
DP	-3.095	0.336	-0.148	1.000		
R	-2.319	0.066	0.176	0.156	1.000	
IRI	-2.979	0.575	-0.038	0.292	0.99	1.000

Table 6-4. . Statistics Values for Equation 4

Variables	t (t_{crit} = -2.005)	Correlation coefficients					
		LC	TC	DP	F	COB	JD
LC	-5.857	1					
TC	-4.080	-0.081	1				
DP	-3.220	0.193	-0.690	1			
F	-3.616	-0.267	-0.414	0.204	1		
COB	-2.209	-0.051	-0.365	0.103	0.191	1	
JD	-2.685	-0.107	-0.279	0.225	0.149	0.221	1

UPCI for both types of pavements included distresses that represent the structural and functional behavior of urban pavements. All distresses in the equations have a high significance in the regressions with the t value higher than the t critical value. In addition, distresses with statistical importance coincide to those observed with high frequency in the field, and were considered as the most important by the expert panel.

It can be observed that deteriorated patches have an important effect in the UPCI value for all UPCIs calibrated. This outcome is coherent and consistent to the phenomena observed in urban pavements, where utility cuts are frequently observed, resulting in low quality patches and high probabilities of premature deterioration. This conclusion supports the primary hypothesis that special condition evaluation guidelines and indicators should be developed for urban pavements.

Comparing the UPCI equations for asphalt pavements, the coefficients for cracking in the $UPCI_{MANUAL}$ are slightly higher than the ones obtained in the $UPCI_{AUTO}$ equation. This can be explained by the fact that cracking in the semi-automated data analysis present lower severity than manual evaluations (21). It is observed, however, that in the $UPCI_{AUTO}$ equation, rutting and IRI coefficients cover the error induced by lower severity cracking. Furthermore, it is assumed that the rutting and IRI in $UPCI_{AUTO}$ equation also represents the effect of potholes, which is absent in the automated equation.

In the case of the concrete equation it is shown to have a high coefficient of faulting, which is due to the use of a different measuring unit, measured in millimeters, than the other distresses in the equation, which are mostly expressed in terms of percentage of the affected area.

Based on the following technical analysis, distresses with positive coefficient or low significance in the regression were eliminated from equations:

For asphalt pavements:

- Edge, block, and longitudinal cracking are distresses with very low frequency in the sample sections evaluated. This makes sense due to the presence of sidewalks in urban pavements and the absence of treated granular base in the evaluated network.
- Shoving also presents a low frequency because of the use of concrete pavements in areas with heavy traffic with low speed, such as bus stops and corners in the evaluated network.
- Bleeding, raveling and polished aggregate are distresses with low significance in network level analysis for urban pavements. These distresses are important for project level analysis.

For concrete pavements

- Durability cracking and blowups are distresses with very low frequency in the evaluated sample sections, which is due to the climate condition in the network evaluated
- Map cracking, scaling, polished aggregate and popouts are distresses with low significance in network level analysis for urban pavements. These distresses are important for project level analysis

For both pavements

- The effect of curb deterioration, water bleeding and pumping, manholes and catch basins are represented by other distresses as fatigue cracking and rutting for asphalt, and oblique cracking and faulting for concrete.

The equations were tested with different values of distresses to check the effect in the UPCI value, giving coherent results for medium values but not for extreme conditions (high and low UPCI). It was identified that further analysis is required to define extreme limits for distresses (maximum or minimum), considering that extreme conditions may affect the calculated condition with the developed equations.

6.4 Qualitative Scale for UPCI

The determination of a qualitative scale for UPCI was carried out from the analysis of the qualitative assessments made by the expert panel.

Qualitative assessments were given by five different conditions: Very Good, Good, Fair, Poor and Very Poor. This evaluation was made separately for primary and secondary network from the local network.

The analysis developed consisted of the study of frequencies of qualitative scales assigned to each quantitative note (1 to 10).

The difference in scale between the two types of scales occurs at lower levels, where the pavements have a bad condition with quantitative ratings between 1 and 4. Therefore, for both networks it is recommended to adopt a common scale designated as for all types of pavement and is presented in Table 6-5.

Table 6-5. Qualitative Scale for UPCI

Primary and Secondary Networks				
UPCI	**Pavement Type**			
	Asphalt	**Concrete**	**Interlocking**	**Recommended for all types**
1	VB	VB	VB	VB
2	VB	VB	VB	VB
3	VB	B	B	B
4	B	B	R	B
5	R	R	R	R
6	R	R	R	R
7	G	G	G	G
8	G	G	G	G
9	VG	VG	VG	VG
10	VG	VG	VG	VG

Local Network				
UPCI	**Pavement Type**			
	Asphalt	**Concrete**	**Interlocking**	**Recommended for all types**
1	VB	VB	VB	VB
2	VB	VB	B	VB
3	B	B	B	B
4	R	R	R	R
5	G	G	G	G
6	G	G	G	G
7	G	G	VG	G
8	VG	VG	VG	VG
9	VG	VG	VG	VG
10	VG	VG	VG	VG

6.5 Comparison of UPCI with ICP and DMI

Two of the indices presented in section 2.2.2 were chosen to compare their results with the UPCI. The condition of asphalt and concrete pavements sample units were calculated with UPCI models and compared with the indices ICP - Indicador de Condición de Pavimentos (Dictuc S.A. 2006) and DMI - Distress Manifestation Index (Chamorro et al. 2009b). These indices were selected for this comparison due to they were calibrated following similar methodologies with the UPCI for the data collection and analysis.

In Figure 6-5 is presented the comparison between the UPCI versus the ICP and DMI for asphalt pavements. It is observed the UPCI delivers higher conditions than ICP and much higher than DMI. These results are marked for fair and low conditions. This could be due to the limits of condition assignation between methodologies, which is higher for interurban pavements.

In the case of concrete pavements, the comparison is presented in Figure 6-6. In this figure is observed the UPCI delivers conditions higher than ICP and lower than DMI. These results when comparing with the ICP could be the same reason of asphalt pavements. When comparing with the DMI could be because the UPCI considers different distresses from DMI as the deteriorated patch that is an important distress for urban pavements.

The models compared could be calibrated for their use in urban pavements but this would imply the same work as the calibration of a new index customized for urban pavements like the UPCI.

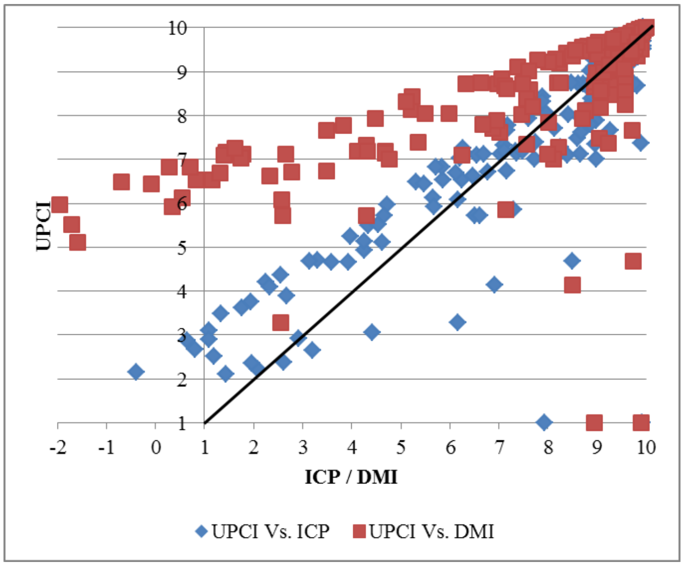


Figure 6-5. Comparison of UPCI Vs. ICP & DMI for Asphalt Pavements

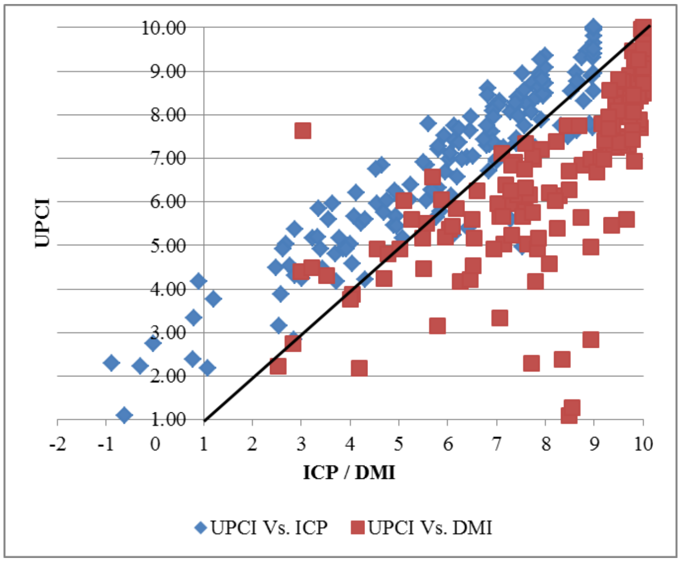


Figure 6-6. Comparison of UPCI Vs. ICP & DMI for Concrete Pavements

6.6 Summary and Recommendations for UPCI use and Urban Pavement Evaluation Methodology

Four final equations were obtained. In the case of asphalt pavement, for manual and automated data collection and a combination of distresses collected manually with IRI, whereas in the case of concrete pavements, for manual data collection

It is recommended that, in the case of application of the developed equations, agencies should consider the advantages and limitations of assessing the network manually or automatically. The use of automated UPCI equation for asphalt pavements it is recommended when IRI values are available. If that is not the case, the Manual UPCI equation considering manual or automated data is recommended due to it includes the potholes.

In the case of concrete pavements, the $UPCI_{MANUAL}$ equation is recommended for manual or automated data. However, further research is recommended to be held in order to obtain an Automated UPCI equation for concrete.

A sensitivity analysis was also performed. The UPCI equations were tested with different distress values to check the impact over the estimated UPCI. Furthermore, in order to transfer results of the analysis to the authorities and to the public, and with the aim of capturing the sensitivity of the methodology, quality values of UPCI related to different network hierarchies were defined.

Recommendations about the frequency and sampling for pavement condition evaluation are the following:

- Primary Network: every 2 year, the complete network
- Secondaty Network: every 4 year, the complete network
- Local Network: every 4 year, samples of homogeneous sections

Chapter 7

Development and Validation of Performance Models

This chapter presents the analysis carried out for the development and validation of performance models. First, the methodology followed is presented. Then, the analysis and results are discussed.

Part of the work presented in this chapter was presented at the 94th Transportation Research Board annual meeting, and published in the proceeding of the conference (Osorio et al. 2015).

7.1 Hierarchies Analysis

In the first stage, the data collected for asphalt and concrete pavements were separately analyzed by hierarchies based on the functional classification. The UPCI evolution over time within the hierarchies exhibited high variability with illogical patterns. These results can be explained by real pavement demands, which in some cases are designed for particular hierarchy characteristics, but the real use of the road in terms of traffic loads does not always correspond to the design.

Pavement design standards in Chile define levels minimum levels of equivalent axles for functional classification. However, functional classification of streets is not defined by the demand of structure for traffic loads support but for the strategic importance of them within the network. Table 7-1 summaries the variability of structure and trucks traffic for each functional classification. This information was obtained from FWD evaluations, core samples and traffic counts.

Table 7-1. Distribution of Structure and Traffic within Functional Classification

Functional Classification	Thickness (mm)	Trucks AADT
Express	57 - 203	1161 - 11709
Troncal	54 - 180	196 - 14330
Colector	50 - 145	1511 - 4941
Service	42 - 152	123-10183
Local	47 - 187	94 - 1042

For the reason aforementioned, hierarchies based on functional classification was used with the classification grouped in the following networks:

- Primary Network for Express and Troncal classification
- Secondary Network for Colector and Service classification
- Local Network for local streets and passages

These network classifications were used only for Mediterranean climate due to the information about sections with dry and humid climate was not enough to make this analysis.

Additionally, a comparative analysis was performed between the real equivalent axles demanding the sections and the equivalent axles admitted by their structures. The real equivalent axles were calculated with the traffic counts data. The admitted equivalent axles were determined through the structural design standards, with the data collected about the structure thickness and strength from the FWD evaluations and core samples.

Results of this analysis showed two different scenarios for Mediterranean climate network for asphalt and concrete pavements: (1) sections where the traffic demand maintains within the range of the structure capacity, and; (2) sections where the traffic demand exceeds the structure capacity. In the analysis of dry climate for asphalt pavements and humid climate for concrete pavements, not enough information was available to make this analysis possible.

These scenarios could be used for Mediterranean climate when information about traffic and structures is available; when not, the other scenarios will be easy to use based on the functional classification.

7.2 Climate Effect

Data collected for asphalt pavement in humid climate and concrete pavement in dry climate was not enough to calibrate the models; however the data of the Mediterranean climate was used to simulate the performance in the other climates.

The seasonal variations in the Mediterranean climate are similar to the related to other climates, presenting a winter season with mean monthly precipitation greater than 200 mm, which can be associated with humid climate; and a summer season with mean monthly precipitation less than 20 mm, comparable to dry climate (Chamorro and Tighe 2011). Therefore, the effects in UPCI after winter and after summer were analyzed as the expected for humid and dry climate, respectively.

For humid climate, the slopes of the UPCI deterioration trend after winter were analyzed, comparing the evaluations performed before and post winter season (June 2012 and January 2013). For dry climate, the differences between the total deterioration during one-year period and the winter period were considered.

Based on the mean value of slopes, the deterioration trends were determined. The deterioration trend of asphalt pavement in humid climate is represented by the 15th percentile of the simulated data of Mediterranean climate; as well as concrete pavement in dry climate is represented by the 75th percentile.

7.3 Calibration of Performance Models

Markov chains with Monte Carlo Simulations were applied for the development of the performance models. The basic principle of Markov chains is to determine Transition Probability Matrices (TPMs) that reflect the future condition of a pavement section that is subject to an initial condition stage (Chamorro and Tighe 2011). These matrices were developed with the data collected in the field during the study period for each scenario considered using the proportions technique (Tjan, A. and Pitaloka, D. 2005).

TPMs were performed considering nine ranges of UPCI: from 1 to 1.9 to 9 to 10. The TPMs represent the proportion of pavements that vary from an initial condition i to a future condition j during a one-year period, given the total length for each state i. The sum of each row yields 100 %.

The following step was the definition of the Cumulative Probability Matrices (CPMs). These matrices were created based on the TPMs, by summing the probabilities for each initial condition, namely, by summing the probability j per row.

Examples of the TPM and CPM developed in the research are presented in Table 7-2 and Table 7-3. All the TPM and CPM developed are presented in Appendix G.

The following assumptions were made for the development of the TPM and CPM in order to make the simulation possible:

- The sections that present an UPCI higher than the last year were eliminated from the analysis
- All sections of the lower range (1.99 – 1.00) remains in this condition
- In ranges of conditions without data available, all sections will be in the range below in the next year
- When all sections present a future condition equal to the current condition, 90% was kept in the current condition and 10% moved to the future condition
- Monte Carlo simulations were performed to obtain the deterioration models. The simulations were performed considering 25 years. A total of 1,000 trials were simulated by random numbers between 0% and 100%. One trial is considered to be a set of 25 random numbers. Each random number represents the cumulative probability that a pavement section with condition i will exhibit condition j after one year of distress progression.

Table 7-2. TPM for Asphalt Pavement Mediterranean Climate Primary Network

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	89	11	0	0	0	0	0	0	0	100
8.99 - 8.00	0	43	57	0	0	0	0	0	0	100
7.99 - 7.00	0	0	0	47	53	0	0	0	0	100
6.99 - 6.00	0	0	0	23	53	0	23	0	0	100
5.99 - 5.00	0	0	0	0	82	18	0	0	0	100
4.99 - 4.00	0	0	0	0	0	0	0	0	0	0
3.99 - 3.00	0	0	0	0	0	0	0	0	100	100
2.99 - 2.00	0	0	0	0	0	0	0	50	50	100
1.99 - 1.00	0	0	0	0	0	0	0	0	0	0

Table 7-3. CTM for Asphalt Pavement Mediterranean Climate Primary Network

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	89	100	100	100	100	100	100	100	100
8.99 - 8.00	0	43	100	100	100	100	100	100	100
7.99 - 7.00	0	0	0	47	100	100	100	100	100
6.99 - 6.00	0	0	0	23	77	77	100	100	100
5.99 - 5.00	0	0	0	0	82	100	100	100	100
4.99 - 4.00	0	0	0	0	0	0	100	100	100
3.99 - 3.00	0	0	0	0	0	0	0	0	100
2.99 - 2.00	0	0	0	0	0	0	0	50	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

The simulation for each trial begins by considering a new pavement section with a UPCI value of 10. Then, the UPCI of this pavement section after a one-year period is determined by introducing the first random number of the trial in the CPMs. This number is verified from left to right in the first row of the CPM (condition from 10 to 9); the first cumulative probability that exceeds the random number is the point to stop; the condition j of that column corresponds to the pavement section after one year of distress deterioration.

The second random number is introduced in the row of new condition determined in the previous step. Then, the condition j after a second year of distress deterioration corresponds to the column of the first cumulative probability that exceeds the random number. This iteration is repeated for the 25 random numbers of the trial. The simulation ends after the 1,000 trials are simulated.

Once the conditions for all trials were determined, the trends were linearized within each condition range given that the CPMs are defined for a range of UPCI. The slope of the deterioration trend was considered -1/(n+1), where n is the number of repeated conditions within a range.

Finally, the models are obtained by the mean of the data simulated and linearized.

As a result of the analyses, fourteen performance models were calibrated from the probabilistic analysis of the field data and the simulation process aforementioned. The curves of these models are presented in Figure 7-1 to Figure 7-14, representing different combination of climate, pavement type, traffic and structure.

In these graphs, the representative value is the mean of the data simulated and the 25th and 75th percentile are also showed as the range of variation of each model. This range for asphalt pavement in humid climates and concrete pavements in dry climates is not presented because these models were obtained by percentiles of the Mediterranean climate.

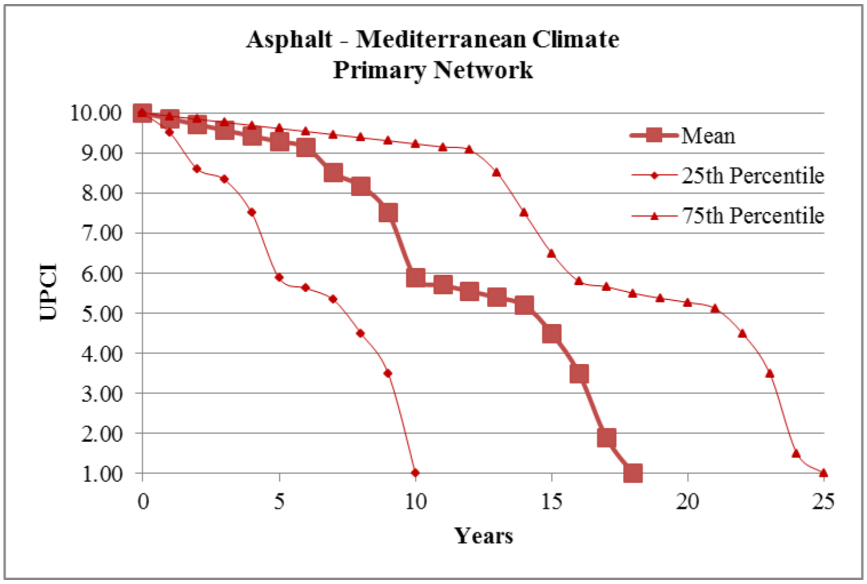


Figure 7-1. Performance Model Asphalt Pavement-Mediterranean Climate-Primary Network

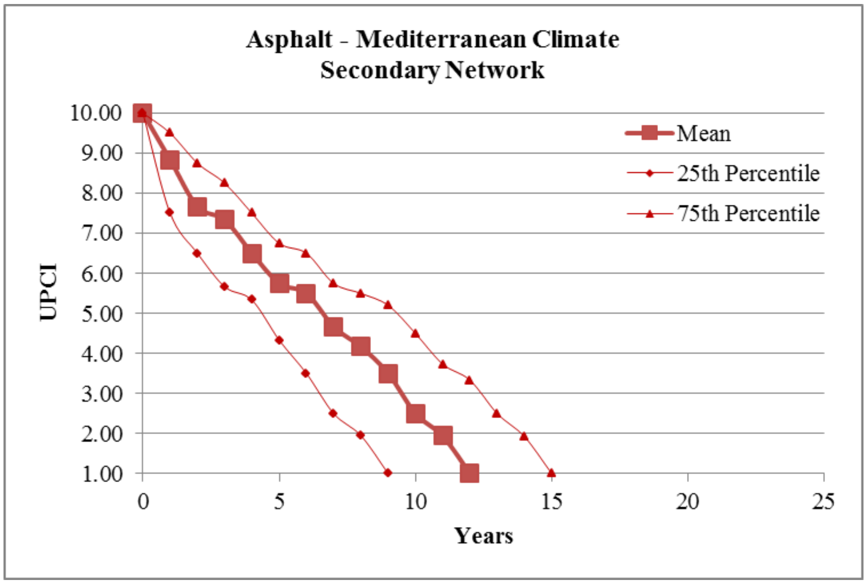


Figure 7-2. Performance Model Asphalt Pavement-Mediterranean Climate-Secondary Network

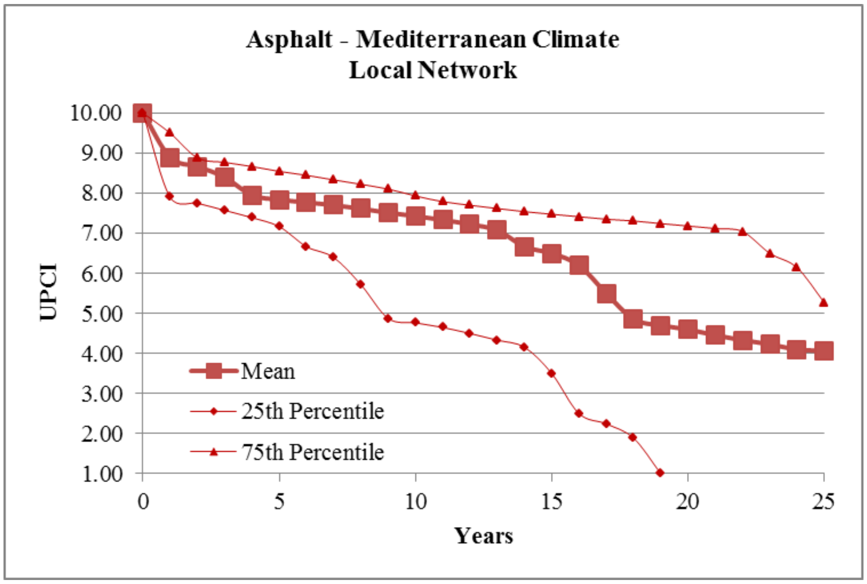


Figure 7-3. Performance Model Asphalt Pavement-Mediterranean Climate-Local Network

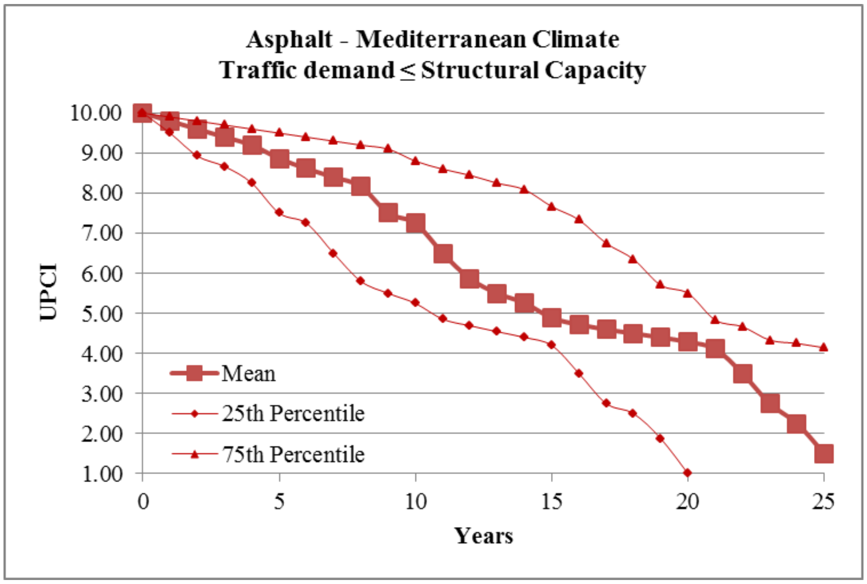


Figure 7-4. Performance Model for Asphalt Pavement-Mediterranean Climate-TD ≤ SC

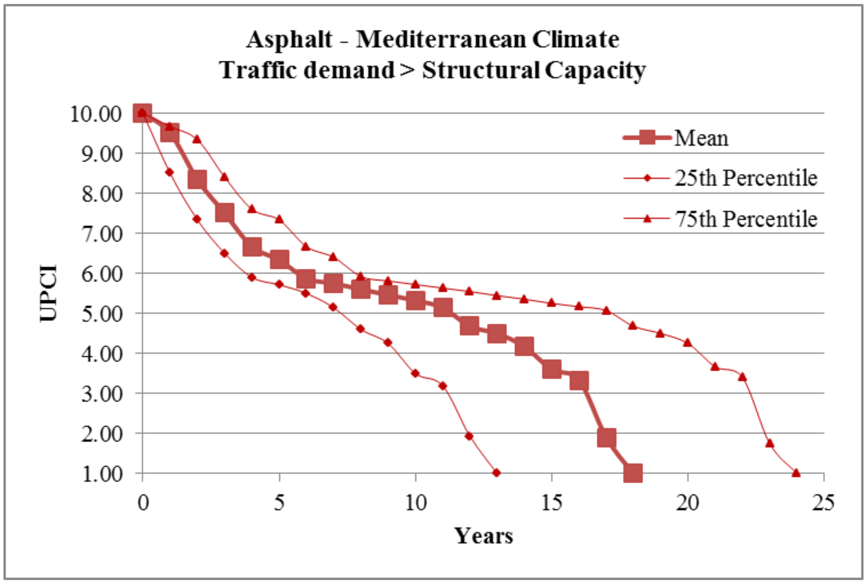


Figure 7-5. Performance Model for Asphalt Pavement-Mediterranean Climate-TD > SC

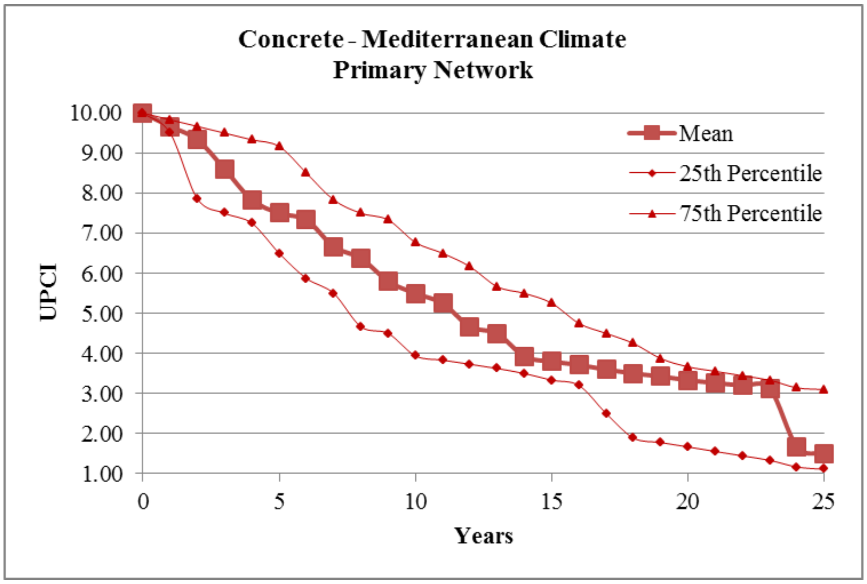


Figure 7-6. Performance Model Concrete Pavement-Mediterranean Climate-Primary Network

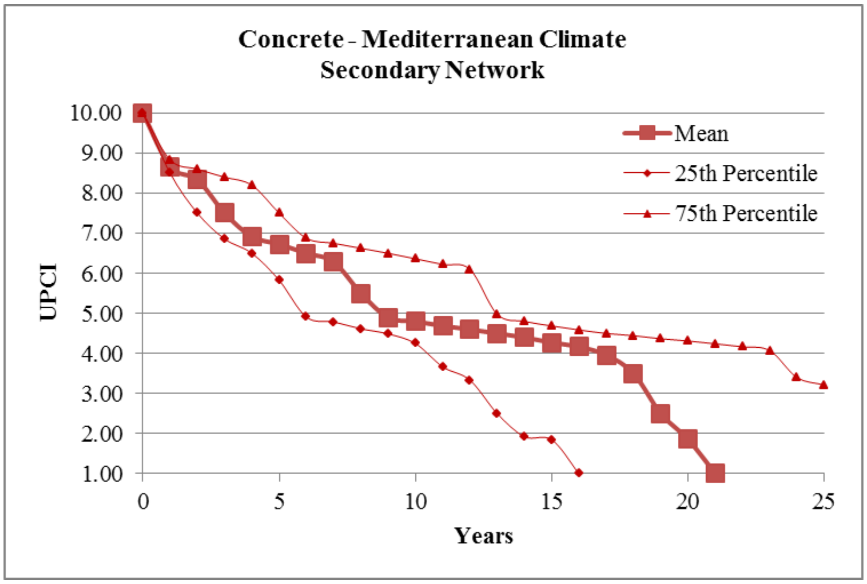


Figure 7-7. Performance Model Concrete Pavement-Mediterranean Climate-Secondary Network

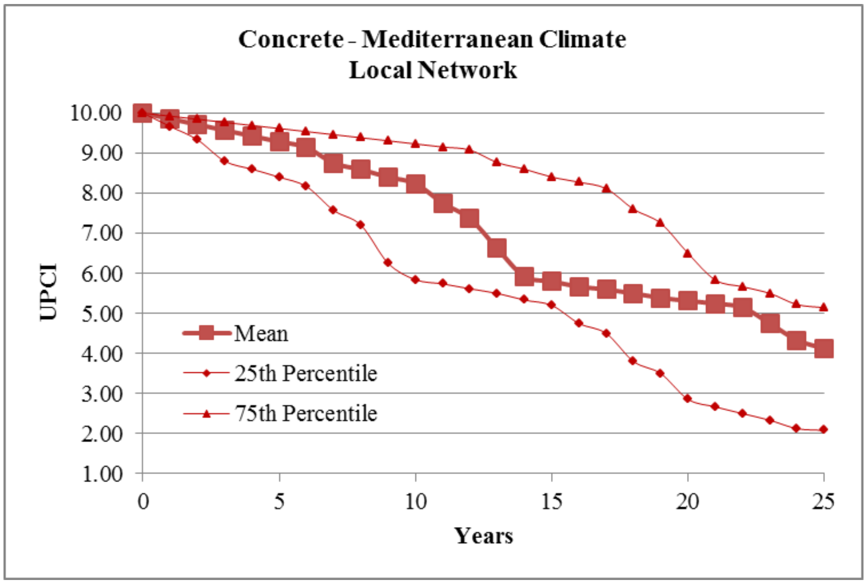


Figure 7-8. Performance Model Concrete Pavement-Mediterranean Climate-Local Network

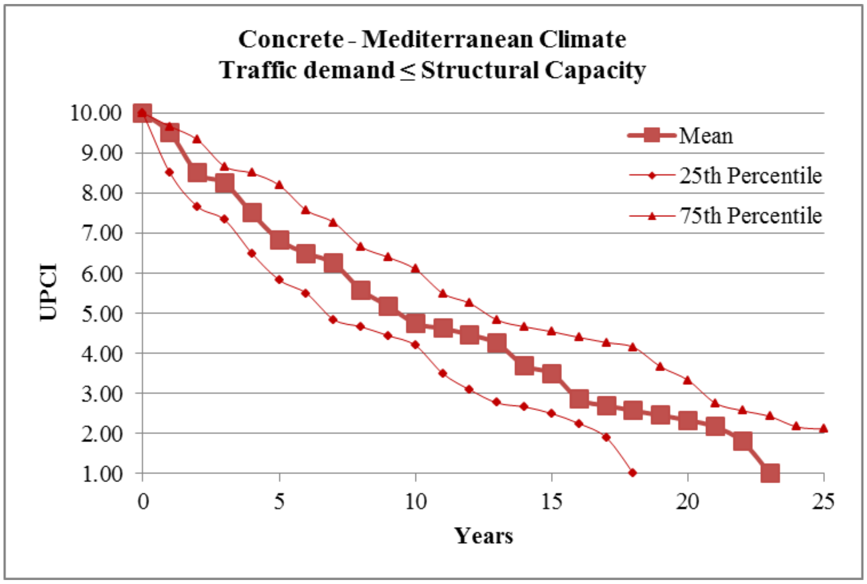


Figure 7-9. Performance Model Concrete Pavement-Mediterranean Climate-TD ≤ SC

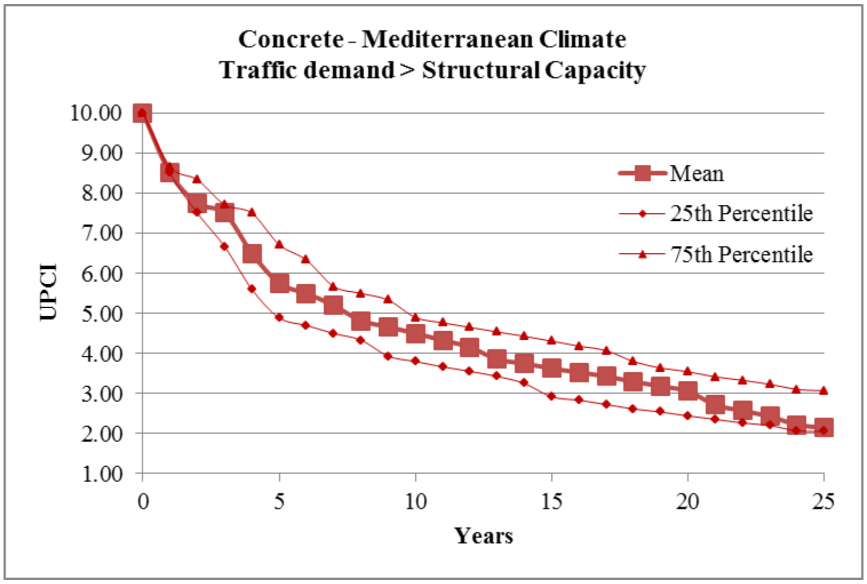


Figure 7-10. Performance Model Concrete Pavement-Mediterranean Climate-TD > SC

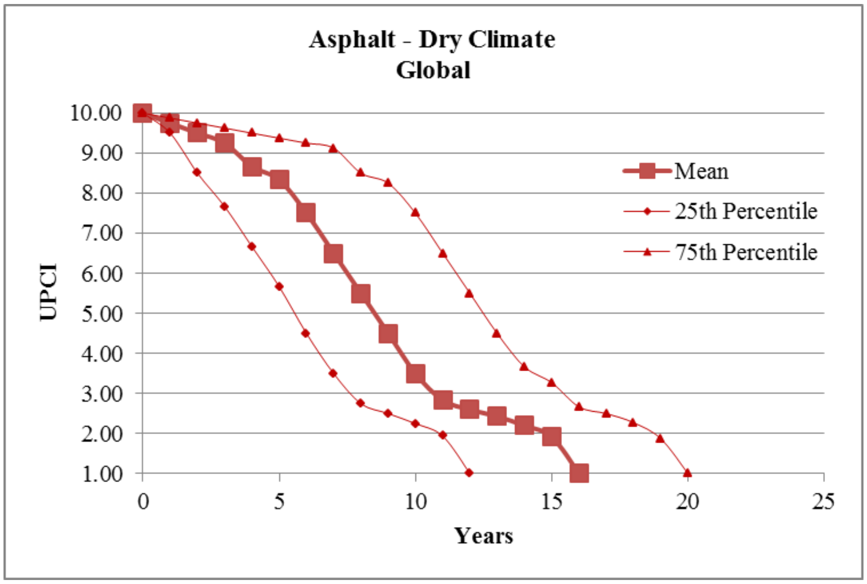


Figure 7-11. Performance Model for Asphalt Pavement-Dry Climate

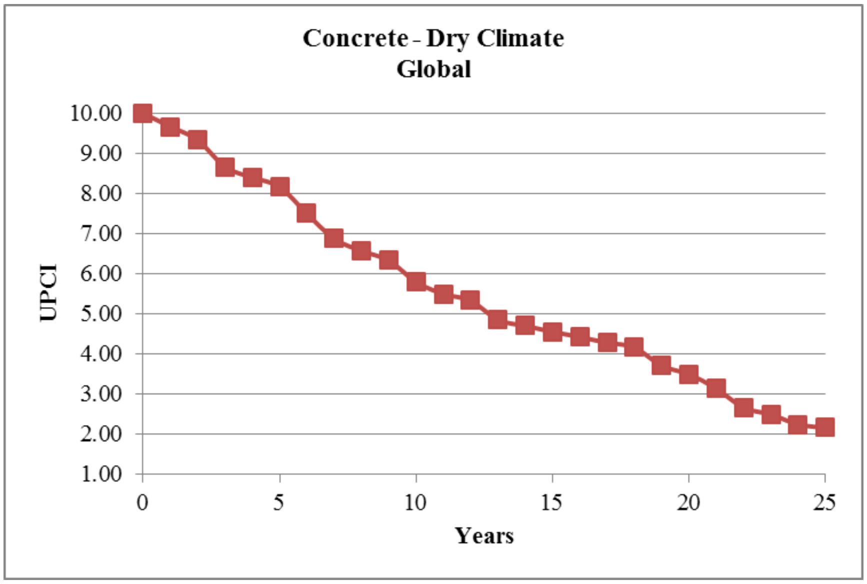


Figure 7-12. Performance Model for Concrete Pavement-Dry Climate

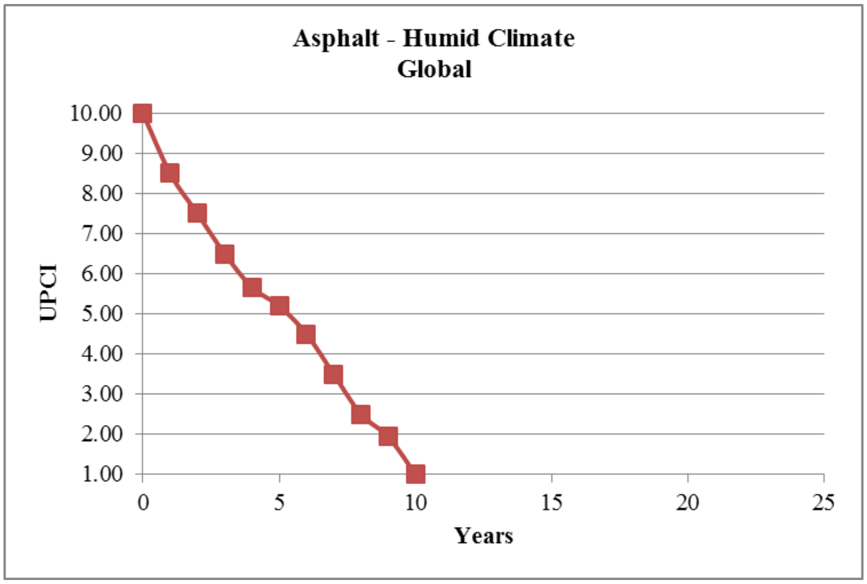


Figure 7-13. Performance Model for Asphalt Pavement-Humid Climate

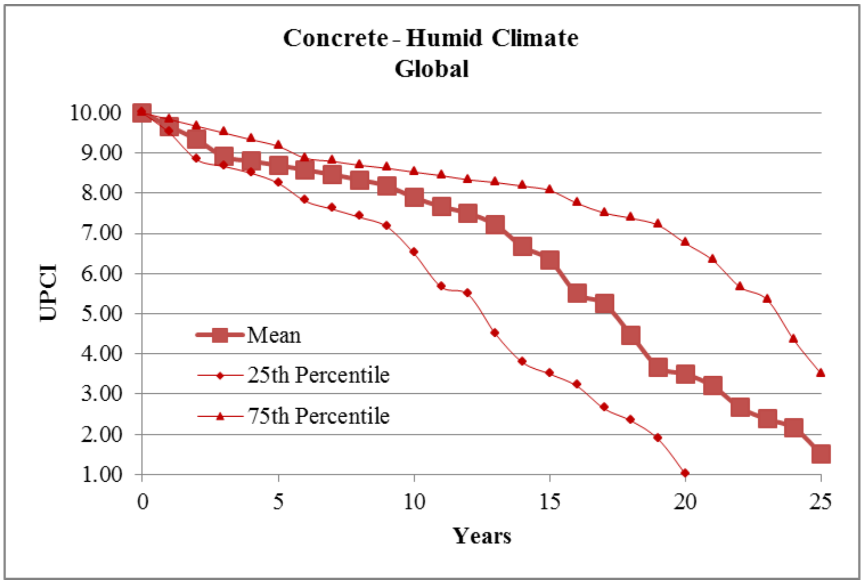


Figure 7-14. Performance Model for Concrete Pavement-Humid Climate

7.4 Performance Models Adjustments

An important process of the calibration of performance models was the adjustments made with data collected and the probabilistic analysis. This process was an iterative analysis, which has included the following activities:

- Regroup data collected in factorials designs and recalibrate in terms of hierarchies: Hierarchies analysis comprised the classification of data in terms of AADT and Structure. As mentioned above, this classification gave high variability of the UPCI evolution over time with illogical patterns within the hierarchies. Finally, an analysis of the relation between the traffic demand and structural capacity was performed to classify the data collected for the probabilistic analysis.
- Service life forced to performance life: The service life was forced to end based on trend observed in curves and design age. This analysis was needed because the process of linearization always ends at 25 years period.
- Recalibration with back simulation: This analysis was carried out to compare the results of probabilistic analysis going from the end of the service life to the beginning. It did not gave better results than the forward simulation.
- Recalibration with Cumulative Probability immediately bellows random number: This recalibration was performed to compare the results of Markov chains with the random number below that the usually use in the method. The results were not better than the traditional method.
- Analysis of probability distribution in TPMs related to distresses: The analysis of distresses triggering values in probability distribution of TPMs was performed to understand the cases presenting simulation problems.

As a result of this adjustment process, the performance models presented in the previous sections were obtained.

7.5 Performance Models Validation

The validation of performance models was performed with 25% of the collected data. t-Tests for comparison of means of the UPCI calculated by the model and the UPCI evaluated in the field were performed considering a one-tailed distribution with a confidence level of 95%.

In the case of Mediterranean climate, the validation was also performed with data collected months after the data used for the calibration of the models to validate the use of the models for extrapolation over time.

Table 7-4 presents the statistic values resulted from the t-test analysis. The models for asphalt pavement in Mediterranean and dry climate and concrete pavements in Mediterranean and humid climate were validated successfully.

Table 7-4. Statistics Values from Performance Models Validation

Climate	Pavement	Network	t_{crit}	t	p value
Mediterranean	Asphalt	Primary	1.7247	0.1938	0.4241
		Secondary	1.7340	0.2908	0.3873
		Local	1.7056	-0.2103	0.4175
		Traffic demand ≤ Structure Capacity	2.0106	-0.1364	0.4460
		Traffic demand > Structure Capacity	2.2281	0.2103	0.4188
	Concrete	Primary	1.6820	-0.0561	0.4777
		Secondary	1.6829	0.1760	0.4306
		Local	1.7341	-0.1142	0.4551
		Traffic demand ≤ Structure Capacity	1.9853	-0.1247	0.4505
		Traffic demand > Structure Capacity	2.1604	-0.0210	0.4918
Dry	Asphalt	Global	1.6698	0.0839	0.4669
Humid	Concrete	Global	2.0369	0.3688	0.3574

The models for asphalt pavement in humid climate and concrete pavement in dry climate were not validated due to these models were estimated from data evaluated in Mediterranean climate. The validation of these models is recommended for future studies.

Figure 7-15 to Figure 7-18 present the comparison between the UPCI evaluated in the field and the UPCI calculated by each model.

The general trend for asphalt pavement is that the UPCI evaluated is a little higher than the UPCI calculated with the models, more accentuated for the primary network.

In the case of concrete pavement, the UPCI evaluated is a little lower than the UPCI calculated with the performance models, mainly for the secondary network and the case of Traffice Demand > Structural Capacity.

In addition, future studies are recommended to validate the models in the following cases:

- In the ranges with no data available in this research, for example lower values of UPCI in the cases of local network and Traffic Demand > Structural Capacity for asphalt pavements and almost all the case but Traffic Demand ≤ Structural Capacity for concrete pavements.
- In the cases where a few data was available for validation, for example Primary Network and Traffic Demand > Structural Capacity for asphalt pavements, and Traffic Demand > Structural Capacity for concrete pavements.

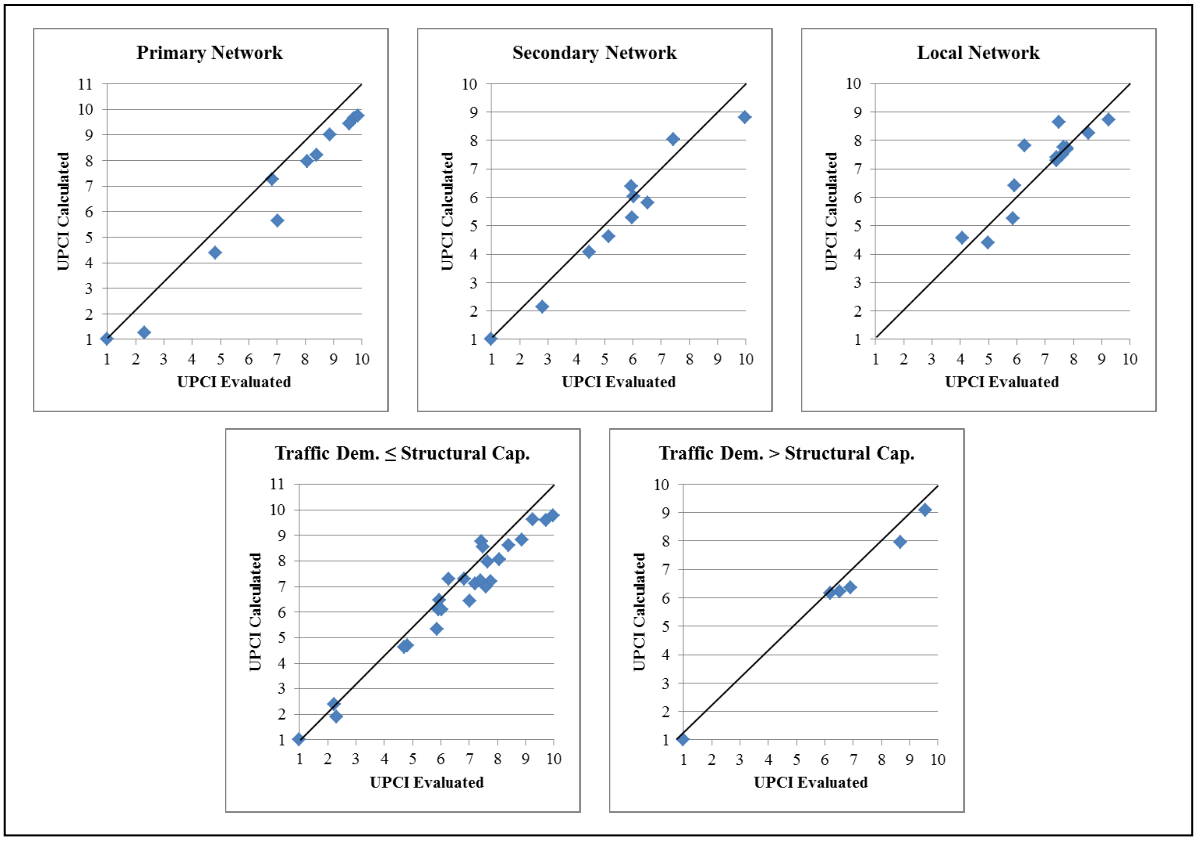


Figure 7-15. UPCI Evaluated Vs. UPCI Calculated Asphalt Pavement-Mediterranean Climate

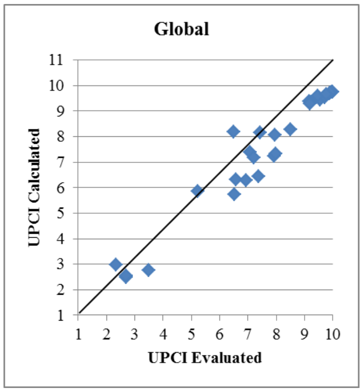


Figure 7-16. UPCI Evaluated Vs. UPCI Calculated Asphalt Pavement-Dry Climate

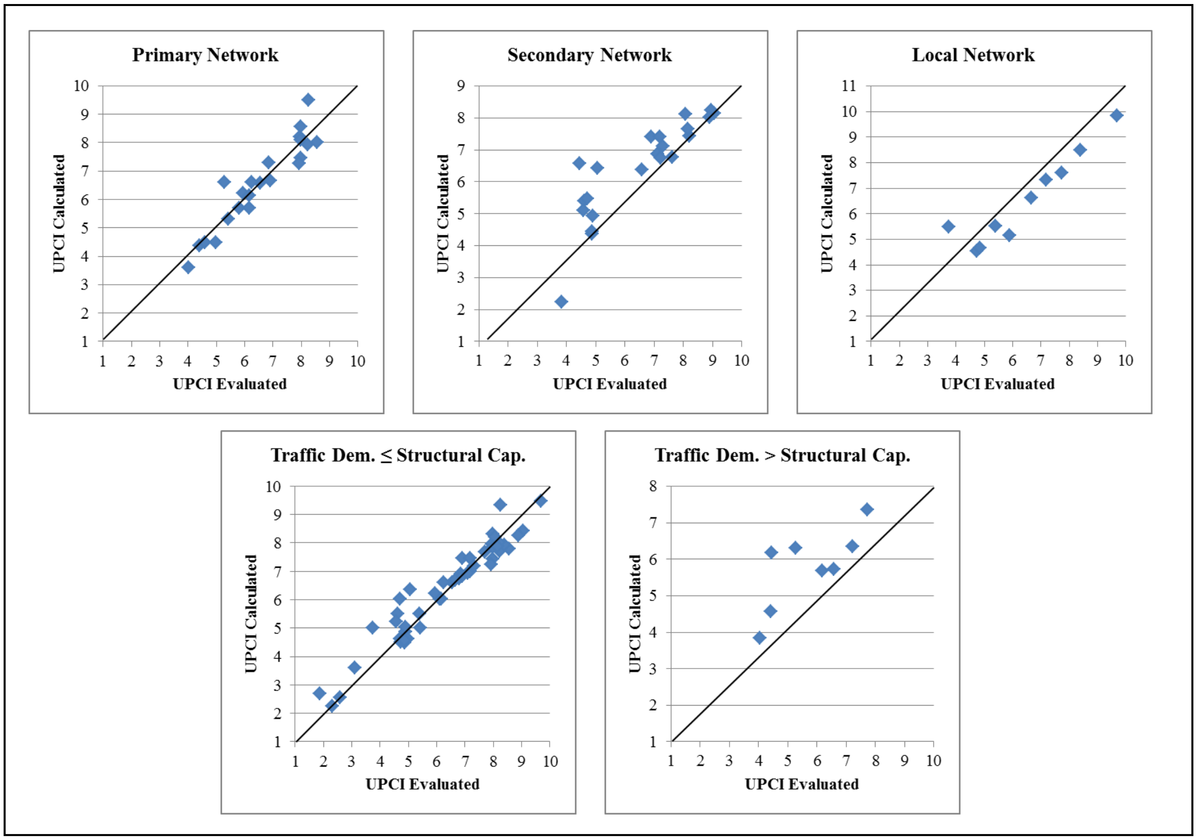


Figure 7-17. UPCI Evaluated Vs. UPCI Calculated Concrete Pavement-Mediterranean Climate

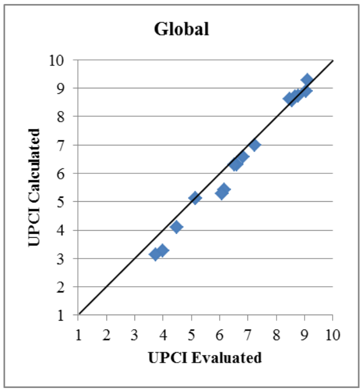


Figure 7-18. UPCI Evaluated Vs. UPCI Calculated Concrete Pavement-Humid Climate

7.6 Main Findings and Recommendations for the use of performance models

Markov chain and Monte Carlo Simulations were carried out for the development of the performance models. Finally, fourteen performance models were developed for different combination of climate, pavement type, traffic and structure. Twelve of them were successfully validated. The timeframe of pavement life cycle considered for the models development was 25 years.

The technique of Markov chain facilitates the analysis of the deterioration trend with only two points of the curve condition over time. This was a huge benefit to simulate the pavement performance within the timeframe of the research. Based on the work of the calibration with this method, it can be concluded that the distribution of proportion within the Transition Probability Matrices is a key aspect for the calibration of models; therefore, a good representation of the network is important to obtain realistic results.

In the Figure 7-19 is presented the comparison of models resulted for asphalt pavements in Mediterranean climate. It can be observed that the Primary Network for asphalt pavements is consistent with the design of 20 years as well as the shape of the deterioration curve follows an expected form. The Secondary Network shows more rapid deterioration than expected, apparently because the streets within this classification could be sub dimensioned for the real demand. On the contrary, the Local network presents a low deterioration rate and this behavior could be due to over dimensioned of the streets.

Considering the models resulted from the analysis of the design, when the traffic demand remains within the structural capacity of the pavement, the UPCI deterioration over time is slower, resulting in a service life of 25 years. However, when the traffic demand exceeds the structural capacity the deterioration over time is steeper. This results in a service life of approximately 16 years, which means 9 years less than the first case. These performance models are recommended to use when information about traffic and structure is available. On the contrary, the models developed based on the functional classification networks are recommended.

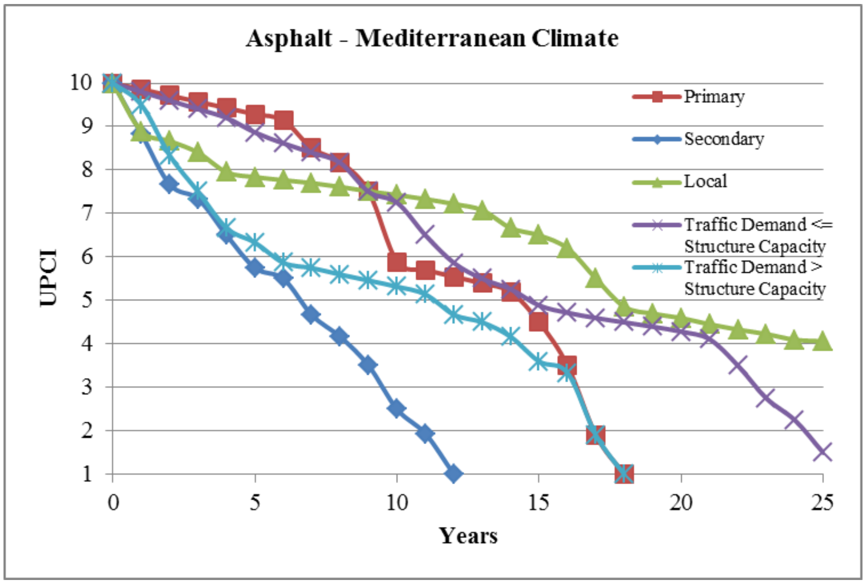


Figure 7-19. Performance Models Asphalt Pavement – Mediterranean Climate

The models resulted for concrete pavement in Mediterranean climates is presented in Figure 7-20. It is observed that Primary and Secondary networks show similar performance with a service life of 25 and 21 years. On the other hand, the Local Network presents very low deterioration rate.

In the case of the design analysis, the deterioration trend does not present big differences within the two conditions analyzed as it can be observed. This phenomenon can be explained by the fact that when traffic demands exceeds structural capacity for concrete pavements the difference is not very extreme as occurs in the case of asphalt pavements. Also, it can be observed that the model curve when the traffic demand exceeds the structure capacity after UPCI = 4, the deterioration trend is slower than the other cases. This is explained by the distribution of the sections with poor UPCI in this case.

Therefore, for concrete pavements is recommend the use of the models calibrated based on the functional classification networks.

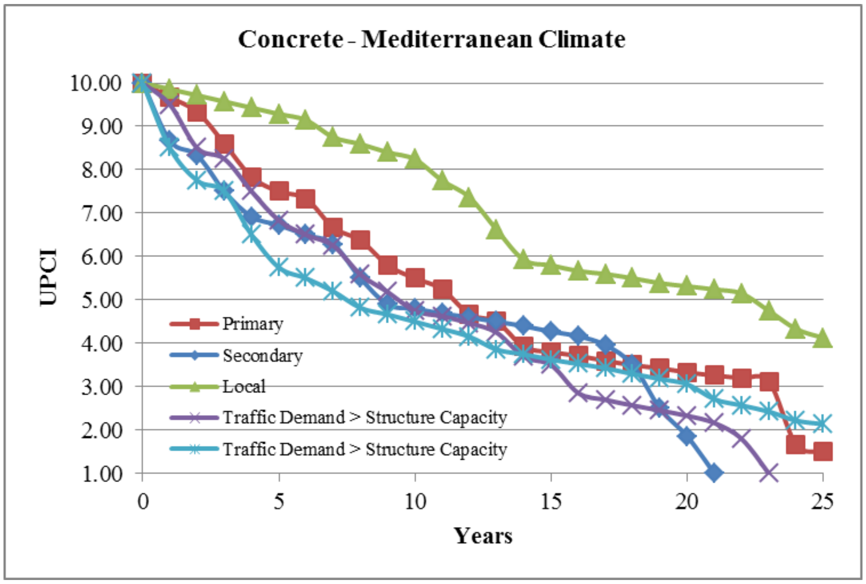


Figure 7-20. Performance models Concrete Pavement–Mediterranean Climate

The performance models calibrated for asphalt pavement in dry and humid climates are presented in Figure 7-21. In the case of dry climate presents slow deterioration between UPCI 10 to 8; then, the deterioration trend is accelerated dropping down from UPCI 8 to 3 in only 6 years; being the total life cycle of 15 years. In the case of humid climate, the deterioration curve is steeper presenting a loose in the UPCI of 1 value/year. However, both models present a shorter service life than their design.

In the Figure 7-22 is presented the comparison of performance models for concrete pavements in dry and humid climates. In the case of humid climate, the deterioration trend presents a gently slope, dropping down from ICPU 10 to 6 in approximately 16 year of service live, achieving 25 of life cycle. In dry climate, the total service life is also 25 year but it presents a deterioration more accelerated than humid climate between UPCI 8.5 to 4.

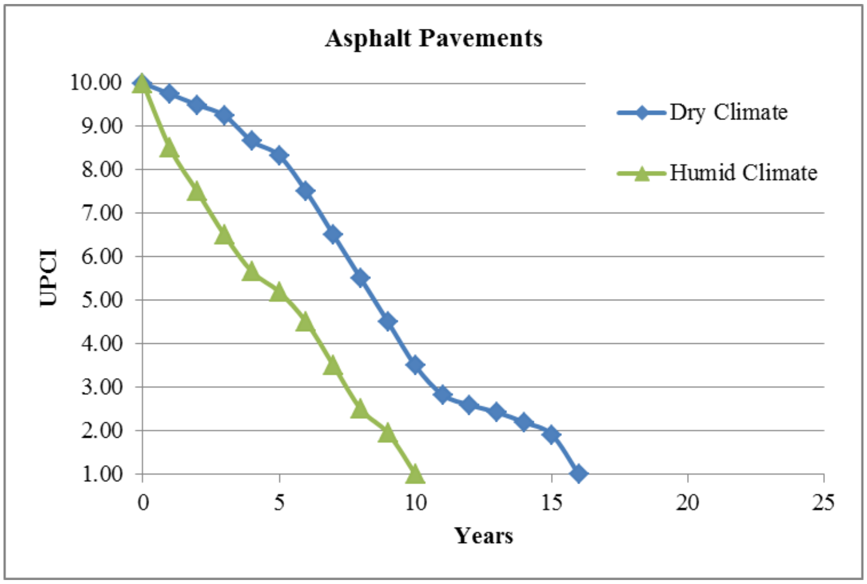


Figure 7-21 Performance Models Asphalt Pavement – Mediterranean and Dry Climate

On the contrary of what is expected for humid climate, the behavior presented is a consequence of the construction standards and maintenance policies, noticed in interviews carried out with agencies of both regions. This result is coherent with the observations of pavement condition in the field.

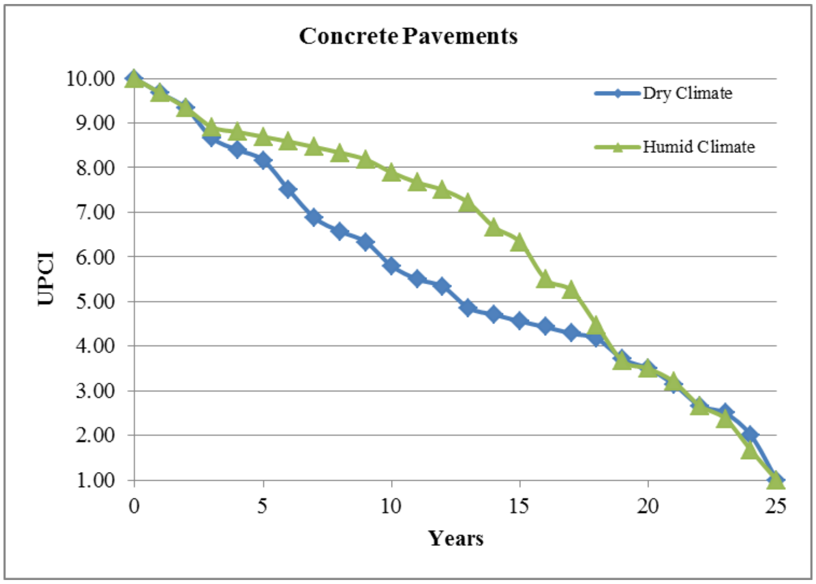


Figure 7-22 Performance Models Concrete Pavement – Mediterranean and Humid Climate

Based on performance models obtained the following conclusions are made about the impacts of climate, traffic and structure: The relation between the traffic demand and the structural capacity has high impact in asphalt pavements deterioration, but low impact in concrete pavements; the climate presents low impact in asphalt pavements comparing global models for Mediterranean and dry climates; however, high impact in concrete pavements. In this latter behavior not only the climate effect is impacting but the construction standards and maintenance policies difference, noticed in interviews carried out with agencies of both regions.

An important recommendation for all the models calibrated in this research is the calibration and validation over time with data collected in the next years in order to retrofit the models with real condition pavement data and improve the deterioration simulation.

Finally, is recommended as future research the calibration and validation of performance models including sections with maintenance activities in order to analyze their performance over time.

Chapter 8

Preservation, Maintenance and Rehabilitation Standards

This chapter presents the P&M&R Standards, which includes the selection of suitable P&M&R treatments for urban pavements, application thresholds in terms of UPCI, effects on the pavement condition, and the maximum UPCI reachable with each action.

Although, the performance models presented in the previous chapter were not developed for different hierarchies, P&M&R Standards are defined for three hierarchies based on streets functional classification: primary (express and troncal streets), secondary (colectors and service streets) and local (local streets and passages).

8.1 Definition of Maintenance Actions for Urban Networks

The definition of the following maintenance actions was performed considering the extend review of current practices of preservation, maintenance and rehabilitation treatments. A summary of maintenance treatments with their characteristics are presented in Appendix I.

8.1.1 Asphalt Pavements

Table 8-1 presents the use of each of them for hierarchy classification.

Table 8-1. Summary of Maintenance Actions selected for Hierarchy – Asphalt Pavements

Type of actions	P&M&R actions	Hierarchy		
		Primary	Secondary	Local
Preservation	Crack Sealing	✓	✓	✓
	Pothole Repair	✓	✓	✓
	Fog Seal	✓	-	-
	Slurry seal	✓	-	-
	Seal Coat	✓	-	-
	Microsurfacing	✓	✓	-
	Functional resurfacing	✓	✓	✓
Maintenance	Hot In-Place Recycling	✓	✓	-
	Cold In-Place Recycling	✓	✓	-
	Structural Resurfacing	✓	✓	✓
Rehabilitation	Reconstruction	✓	✓	✓

The maintenance actions for asphalt pavements are described below, grouped based on their type of maintenance. In addition, the Appendix J presents the references of construction standards used in Chile for the treatments selected.

8.1.1.1 Preservation

- Crack Sealing

Crack sealing consists of the use of asphalt to seal certain cracks in asphalt pavements for the purpose of minimizing the infiltration of water and the oxidization of the asphalt. This procedure is effective for the treatment of localized cracks of medium to high severity (MINVU 2008a).

- Pothole Repair

Potholes repair encompasses the repair of potholes and the replacement of localized areas that are deteriorated, provided that this effort is limited to the asphalt layer while the gravel and other layers are in good condition (MINVU 2008a).

- Fog Seal

A fog seal consists of a diluted asphalt emulsion that is applied to rejuvenate the pavement surface and thus avoid the loss of aggregate in the asphalt layer (Hicks et al, 2000; Kraemer et al, 2005). These seals are applied when the pavement displays initial signs of wear, such as mild superficial cracking, slight loss of asphalt concrete at the surface, or superficial discoloration of the asphalt characterized by a gray tone (MINVU 2008a; MOP 2014).

- Slurry seal

A slurry seal is a mixture of well-graded fine aggregate, mineral filler (if necessary), asphalt emulsion, and water. It is applied to a pavement as a surface treatment (MINVU 2008a).

Similarly to the fog seal, slurry seals can be applied to seal cracks and fissures. Slurry seals can also be applied to stop superficial pavement deterioration and to improve friction between the pavement and automobile tires (MINVU 2008a; MOP 2014).

The application of the slurry seal requires the preparation of the surface, sealing of existing cracks and filling of existing potholes.

- Seal Coat

The seal coat is a type of surface treatment consisting of a tack coat (composed of a normal or modified asphalt emulsion) followed by a layer of monogranular aggregate (MINVU 2008a).

If the tack coat and a single application of gravel are applied, it is called a single surface treatment (single chip seal). If two applications of gravel are performed with aggregates of decreasing grain size, then it is called a double surface coating (double chip seal) (Gransberg and James 2005; Kraemer et al. 2004).

Initially, these treatments were applied as a wearing course on unpaved roads with low traffic. However, in recent years, their application has been extended to maintenance actions on pavements with high and low levels of traffic (Gransberg and James 2005). Their application as a conservation treatment seals the pavement surface, stops surface deterioration, and improves surface friction (Gransberg and James 2005; Hicks et al. 2000; MINVU 2008a; MOP 2014).

The application of the seal coat requires the preparation of the surface by sealing existing cracks and repairing existing potholes.

- Microsurfacing

Microsurfacing contains the same components as a slurry seal except that the emulsion in microsurfacing is modified with polymers and the gravel is of better mechanical quality. Therefore, this technique is commonly used on important roads (MINVU 2008a).

There are identified three characteristics of micro-surfacing that differentiates it from slurry seals (Gransberg 2010): it always contain polymers; the curing of the emulsion is faster so that the road can be placed back in service in a shorter period of time; and layers thicker than the maximum size of the gravel are available.

This treatment is applied to asphalt pavements with a certain degree of aging (oxidization), for example, rutting and a loss of surface gravel. In addition, microsurfacing allows for the correction of small surface irregularities and improves the friction (Gransberg 2010).

It was decided to include this treatment as a maintenance action for preservation, based on its successful application in countries such as Spain, the United States and Canada (Avilés Lorenzo 2002; Chan et al. 2011; Hicks et al. 2000).

The Spanish standard (TAC 2013) limits the application of MICROF 5 micro-surfacing to a single layer with a thickness usually no greater than 1.5 cm. The common practice in the U.S. is to apply a maximum thickness of two to three times the maximum size of the gravel being used (Gransberg 2010). For a Type II pavement, this practice would limit the thickness of the treatment to a maximum between 1 and 1.5 cm. Based on these considerations, a micro-surfacing thickness of 1.5 cm is considered in this research.

Based on U.S. and Canadian recommendations (Caltrans 2009; TAC 2013), which recommend microsurfacing with fine granulometry for applications on urban pavements, Type B-1 of Chilean standard is considered in this research (MOP 2014). This microsurface is equivalent to Type II of the U.S. norm (Gransberg 2010) and to MICROF 5 of the Spanish standard (MFE 2011).

Microsurfacing requires prior preparation of the surface by sealing cracks and filling potholes.

- Functional resurfacing

Functional resurfacing consists of the replacement of the upper asphalt layer with a hot asphalt mixture (MOP 2014). This treatment improves the condition of the pavement surface, although it does not increase its structural capacity.

Given that this resurfacing raises the height of the road, it is advisable to first mill the surface. The milling consists of wearing away the pavement surface to restore the road level (MINVU 2008a). The milling reduces the pavement thickness, thereby leaving a scarified surface that serves as a base for the resurfacing (MINVU 2008a; MOP 2014). The milling ensures that the resurfaced pavement level will be the same as that before the treatment.

In this research work, it is assumed that sections in the Primary and Secondary network will be milled before the functional resurfacing. However, the pavements of the Local network will not be milled, thus reducing expenses for this treatment.

8.1.1.2 Maintenance

- Hot In-Place Recycling

Hot in-place recycling consists of the softening of the existing asphalt pavement by applying heat and then removing the asphalt through mechanical means. This material is mixed with virgin asphalt and aggregate, thus creating a new wearing course to replace the pavement that was removed (Hicks et al. 2000; TAC 2013).

This treatment is applied when the pavement is highly deteriorated, with symptoms such as detachment of the gravel, secretion, cracks and rutting (TAC 2013).

This treatment it has been considered in the research to include more environmentally friendly alternatives.

- Cold In-Place Recycling

Similar to Hot In-Place and cold recycling uses material from an existing asphalt pavement to create a new wearing course. However, in this case, there is no need to heat the existing pavement for its reuse. Instead, the material is mechanically removed from the pavement in such a way that it can be reused (Thenoux and Garcia 1999).

This treatment is applied to pavements in poor condition and displaying severe levels of cracking, rutting or other deteriorations, thus improving their structural capacities (TAC 2013).

- Structural Resurfacing

Structural resurfacing is similar to the functional resurfacing treatment except that it is thicker to improve the structural capacity of the pavement.

Because structural resurfacing tend to be considerably thick, in this research it has been assumed that the treatment requires the prior milling of the surface for all hierarchies of the networks. Therefore, the pavement elevation will be the same before and after the treatment.

8.1.1.3 Rehabilitation

- Reconstruction

Reconstruction is a technique in which the old pavement is removed and replaced by a new one. In a few instances, the existing pavement is kept, but the structural calculations do not include its contribution (MOP 2014).

8.1.2 Concrete Pavements

Table 8-2 presents the proposed maintenance actions for concrete pavements based on hierarchy classification.

Below, it is described the P&M&R actions for concrete pavements, where they are grouped based on the type of conservation. Furthermore, the Appendix J presents the references of construction standards used in Chile for the treatments selected.

Table 8-2. Summary of Maintenance Actions selected for Hierarchy – Concrete Pavements

Type of actions	P&M&R actions	Hierarchy		
		Primary	Secondary	Local
Preservation	Crack and joint sealing	✓	✓	✓
	Corner Breaks Repair	✓	✓	✓
	Diamond Grinding	✓	✓	-
	Thin Asphalt Overlay	✓	✓	-
	Bonded Concrete Overlay	✓	✓	-
Maintenance	Crack and Joint Stitching	✓	✓	✓
	Full-Depth Slab Repair	✓	✓	✓
	Structural Resurfacing	✓	✓	✓
Rehabilitation	Reconstruction	✓	✓	✓

8.1.2.1 Preservation

- Crack and joint sealing

Keeping joints and cracks sealed is fundamental for achieving the expected useful life of the pavement. For a seal to work properly, it is necessary that the joints and cracks do not undergo significant relative vertical displacements (MINVU 2008a).

- Corner Breaks Repair

Repairs of corners breaks areas are particularly important at the edges of longitudinal or transversal joints. For this purpose, the concrete in the deteriorated area is removed and new concrete is put in place (MINVU 2008a).

- Diamond Grinding

Diamond grinding of concrete pavements reduces irregularities, thereby improving the quality of their service and extending their useful life. This procedure increases the friction between tires and the pavement, and eliminates irregularities created by steps at joints and by deformations due to thermal gradients or construction procedures (MINVU 2008a; MOP 2014).

This treatment does not increase the structural capacity of the pavement, but by minimizing the dynamic effects of loads it allows the structure to withstand a greater number of loading cycles during the rest of its useful life (MOP 2014).

It requires to be applied together with crack and joints sealing, and corner breaks repair.

- Thin Asphalt Overlay

Asphalt overlay for concrete pavements is the same as Functional resurfacing for asphalt pavements described above but without the milling process.

- Bonded Concrete Overlay

Bonded concrete overlay consists of the placement of a thin concrete wearing course, with a thickness of 50 to 125 mm, on top of the existing concrete after it has been treated with Diamond Grinding to ensure adherence. The slabs used in this treatment are squares measuring 0.60 to 1.00 m on a side. It is important that the joints of the recoating coincide with those of the existing pavement (TAC 2013).

Because the application of this type of recoating increases the height of the road and because adherence must be ensured, the prior diamond grinding treatment on the surface is considered.

8.1.2.2 Maintenance

- Crack and Joint Stitching

Crack and Joint Stitching is a treatment that repairs longitudinal, meandering and non-working transverse cracks and longitudinal joints. There are two crack stitching methods: cross stitching and slot stitching. The first is done by drilling diagonally through the slab across the crack or joint and inserting tie bars. The latter, uses cuts similar to dowel bar retrofit to install tie bars across any cracks or longitudinal joints (TAC 2013).

Stitching prevents widening of cracks and joints. Narrow cracks maintain aggregate interlock, reduce the potential of faulting, and are easier to seal. Good candidates for stitching are pavements in good conditions were cracks and joints show signs of slab migration. If longitudinal cracks and joints perform well simply by sealing them, then it is not necessary (TAC 2013). For this reason, this treatment is considered as a maintenance rather than preservation action.

- Full-Depth Slab Repair

Full-depth slab repair consists of removing loose material from concrete pavement that exhibits a high degree of cracking and deterioration (MOP 2014; TAC 2013). Once this material has been removed and the surface is cleaned, fresh concrete is poured on top of the surface.

- Structural Resurfacing

8.1.2.3 Rehabilitation

- Reconstruction

Reconstruction is a technique in which the old pavement is removed and replaced with a new one. The existing pavement is occasionally left in place, but its contribution is not included in the structural calculations (MOP 2014).

8.2 Definition of Maintenance Application Ranges and Effect on UPCI

Each maintenance action must be applied to pavements of a certain condition range (UPCI) in order to obtain optimal results and so that maximum improvement of the pavement condition is achieved.

The definition of UPCI ranges for the application of maintenance actions and the effect on the UPCI was carried out based on:

- Information of distresses that each maintenance treatment fixes: The information includes the type of action, effect in the condition, recommendation of application in term of distresses and thresholds, cost, etc. (See Appendix I).
- Analysis of distresses combination for UPCI ranges: As the maintenance actions found in the state-of-the-art are recommended in terms of particular distresses, an analysis of UPCI variation based on the combination of distresses was performed to define the ranges of application in terms of UPCI.
- Effect of some actions observed in field evaluations: All the maintenance actions evaluated in the field improved the conditions of the sections at the maximum condition of UPCI=10, due to all the maintenance actions evaluated included overlays.

The values of these ranges are presented in Table 8-3 for asphalt pavements and Table 8-4 for concrete pavements.

Table 8-3. P&M&R Actions Applicability Range – Asphalt Pavements

P&M&R Actions	Applicability Range – UPCI		
	Primary Network	Secondary Network	Local Network
Crack Sealing	9 – 8	8.5 – 7.5	7.5 – 6
Pothole Repair	9 – 8	8.5 – 7.5	7.5 – 6
Fog Seal	9.5 – 8.5	-	-
Slurry seal	8.5 – 7.5	-	-
Seal Coat	8.5 – 7.5	-	-
Microsurfacing	8 – 7	7.5 – 6.5	-
Functional resurfacing	8 – 6.5	7.5 – 6	7.5 – 6
Hot In-Place Recycling	7.5 – 5.5	7 – 5	-
Cold In-Place Recycling	7.5 – 5.5	7 – 5	-
Structural Resurfacing	7 – 4.5	6.5 – 4	6 – 3.5
Reconstruction	4.5 – 1	4 – 1	3.5 – 1

Table 8-4. Maintenance Actions Applicability Range – Concrete Pavements

P&M&R Action	Applicability Range – UPCI		
	Primary Network	Secondary Network	Local Network
Crack and joint sealing	9 – 8	8.5 – 7.5	8 – 6
Corner Breaks Repair	9 – 8	8.5 – 7.5	8 – 6
Diamond Grinding	8 – 7	7.5 – 6.5	-
Thin Asphalt Overlay	8 – 7	7.5 – 6.5	-
Bonded Concrete Overlay	8 – 7	7.5 – 6.5	-
Crack and Joint Stitching	7 – 4.5	6.5 – 4	6 – 3.5
Full-Depth Slab Repair	7 – 4.5	6.5 – 4	6 – 3.5
Structural Resurfacing	7 – 4.5	6.5 – 4	6 – 3.5
Reconstruction	4.5 – 1	4 – 1	3.5 – 1

Table 8-5 and Table 8-6 show the values defined for asphalt and concrete pavements, respectively.

Table 8-5. Effects on the UPCI and Maximum UPCI achieved – Asphalt Pavement

P&M&R Action	Effects on the UPCI / maximum UPCI achieved		
	Primary Network	Secondary Network	Local Network
Crack Sealing	0.5 / 9.5	0.5 / 9.0	0.5 / -
Pothole Repair	0.75 / 9.5	0.75 / 9.0	0.75 / -
Fog Seal	0.5 / 9.5	-	-
Slurry seal	1.3	-	-
Seal Coat	1.5	-	-
Microsurfacing	2.0 / 9.75	2.0 / 9.75	-
Functional resurfacing	2.5 / 10.0	2.5 / 10.0	2.5 / 9.5
Hot In-Place Recycling	4.5 / 10.0	4.5 / 10.0	-
Cold In-Place Recycling	4.5 / 10.0	4.5 / 10.0	-
Structural Resurfacing	5.5 / 10.0	5.5 / 10.0	5.5 / 10.0
Reconstruction	9.0 / 10.0	9.0 / 10.0	9.0 / 10.0

Table 8-6. Effects on the UPCI and Maximum UPCI achieved – Concrete Pavement

P&M&R Action	Effects on the UPCI / maximum UPCI achieved		
	Primary Network	Secondary Network	Local Network
Crack and joint sealing	0.5 / -	0.5 / -	0.5 / -
Corner Breaks Repair	1.25 / -	0.75 / -	0.75 / -
Diamond Grinding	2.5 / 9.75	2.5 / 9.75	-
Thin Asphalt Overlay	2.5 / 9.75	2.5 / 9.75	-
Bonded Concrete Overlay	2.5 / 9.75	2.5 / 9.75	-
Crack and Joint Stitching	2.2 / 10.0	-	-
Full-Depth Slab Repair	3.6 / 10.0	3.6 / 10.0	3.0 / 10.0
Structural Resurfacing	4.3 / 10.0	3.7 / 10.0	3.5 / 10.0
Reconstruction	9.0 / 10.0	9.0 / 10.0	9.0 / 10.0

8.3 Considerations for Standards Optimization

The standards recommended as a result of this research are the technical base for the optimization considering other aspects such as economic, environmental, etc., in order to analyze the costs and benefit in the life cycle assessment of urban pavements. The optimization could be carried out using different techniques, including cost-benefit analysis, cost-effectiveness and others.

Next steps for the optimization analysis are: define the technique to performed the analysis; collect the information about costs and characteristics of other aspects to include in the analysis (ex. environmental); and perform the optimization.

Given that the maintenance actions proposed in this research involve UPCI threshold values of applicability with a variation range of 0.5 points, the optimization of standards would need to take into account this UPCI variation range. Therefore, for each deterioration model, the applicable maintenance action alternatives would be applied to 19 possible UPCI values, which correspond to values between 10 and 1 with intervals of 0.5.

In the cases where the UPCI does not coincide with the evaluated values, the optimization must assign the corresponding actions to the next lower value that was calculated. This ensures a conservative assignment of maintenance actions as a function of the pavement condition.

8.4 Summary of the Chapter

Suitable maintenance standards for asphalt and concrete pavements in urban networks were defined in this chapter. These standards included: the maintenance actions with their UPCI range of application, their effects in the UPCI and the maximum UPCI reachable.

The definition of the standards was developed considering the information collected in the-state-of-the-and-the practice-review as well as the data collected during field evaluation of section maintained during the research time frame.

The standards proposed as a result of this research is the technical base for the optimization of the standards based on other aspects such as economic, environmental, etc., in order to analyze the costs and benefit in the life cycle assessment of urban pavements.

The standards must be calibrated over time considering the ranges of application, the effects on the UPCI and the maximum UPCI reachable, for those P&M&R actions that are not currently use in urban pavement conditions. This is important because it can give feedback about the real maintenance effect observed in the field.

Chapter 9

Conclusions and Recommendations

Given the state-of-the-art and the-practice of urban pavement management, there is a need for better understanding of urban pavements performance. Therefore, this research was focused on the analysis of urban pavements at network level, toward the development of practical and sustainable technical tools to be integrated further into an Urban Pavement Management System (UPMS).

Based on the results presented in each chapter of this thesis, it can be concluded that the overall objective of calibrating an Urban Pavement Condition Index (UPCI) and performance models, technical components required for an urban pavement management system, based on data collected in urban networks in Chile, was successfully accomplished by the research.

It also concluded that these practical tools can be easily implemented and used by local agencies, and simply adaptable over time and to different scenarios. The results of the study were developed with field data collected in Chilean cities; however, the results may be adapted and adopted in other countries for urban pavement management. Public agencies involved in the management process and allocation of pavement maintenance resources will be the main users of the results obtained from this research.

The two hypotheses of the research were successfully demonstrated through the fulfillment of the specific objectives:

1. **Calibrate and validate an index representative of the overall condition of urban pavements, Urban Pavement Condition Index (UPCI), considering manual and automated data collection methodologies**

- Urban Pavement Condition Indexes for asphalt and concrete pavement, based on objective measures of surface distresses and evaluations of an expert panel was successfully calibrated and validated with a confidence level of 95%.
- Three UPCI models were obtained for asphalt pavements with manual and automated data collection. The distresses resulted significance in asphalt pavement condition are fatigue cracking, transverse and reflection cracking, deteriorated patches, rutting, and potholes for manual data collected. IRI replaces potholes in the condition equation for automated data collected. Although the UPCI models for manual and automated data were successfully cross-validated, the use of automated UPCI equation for asphalt pavements it is recommended when IRI values are available. If that is not the case, the Manual UPCI equation considering manual or automated data is recommended due to it includes the potholes.
- One UPCI model was achieved with successfully validation for concrete pavements with manual data collection. The distresses representative of concrete pavement condition are longitudinal, transversal and oblique cracking, corner breaks, deteriorated patches, faulting, and deteriorate joints and cracks.
- The UPCI for concrete pavements with automated data did not give satisfactory results. The main reasons were: UPCI equation for automated data does not consider the same distresses included in the UPCI equation for manual data, causing that some distresses are not

represented in the automated equation; possible correlation between independent variables considered in the automated regression may be affecting the regressions, considering distresses and IRI values; difference in the evaluation methodology between manual and automated data collection may be affecting the regressions. Therefore, UPCI equations for concrete pavements considering automated data require further analysis and the UPCI manual is recommended to use with manual and automated data.

- The statistics analysis carried out for interlocking pavement was not successfully validated. This may be explained by these reasons: possible correlation between independent variables considered in the regression, and; the expert panel present high variability in the UPCI observed evaluated in the field. Further analysis is needed to obtain an UPCI for this type of pavement.
- Distress evaluation guidelines for asphalt and concrete pavements considering manual and automated surveys were developed and satisfactory validated with a 95% of confidence level through repeatability and reproducibility analysis. This guideline proposes an evaluation methodology for the distresses included in the UPCI.
- Deteriorated patches have an important effect in the UPCI value for all UPCIs calibrated. This outcome is coherent and consistent to the phenomena observed in urban pavements, where utility cuts are frequently observed, resulting in low quality patches and high probabilities of premature deterioration. This conclusion supports the primary hypothesis that special condition evaluation guidelines and indicators are required for urban pavements.
- Based on the field evaluation carried out during the research, recommendations about the frequency and sampling for pavement condition evaluation are given for different network hierarchies: primary, every 2 year, the complete network; secondary, every 4 year, the complete network, and; local, every four years samples of homogeneous sections.

2. **Calibrate and validate condition performance models for urban pavements representative to different climates, structures, traffic and pavement types**

- Performance models were performed based on probabilistic trends of UPCI observed during field evaluations for asphalt and concrete pavements. The deterioration of this indicator can assist in life cycle cost analyses for decision-making at network level analysis.
- Five field evaluation campaigns were developed in three regions of Chile during a three-year analysis period for the calibration and validation of performance models. The climates included were dry, Mediterranean and humid.
- The probabilistic trend over time of data collected was analyzed using Markov chains with Monte Carlo simulation. The technique of Markov chain facilitates the analysis of the deterioration trend with only two points of the curve condition over time. This was a huge benefit to simulate the pavement performance within the timeframe of the research. Based on the work of the calibration with this method, it can be concluded that the distribution of proportion within the Transition Probability Matrices is a key aspect for the calibration of models; therefore, a good representation of the network is important to obtain realistic results.
- Fourteen performance models were calibrated for different combination of three climates, two pavement types and three hierarchy networks, considering a pavement life cycle of 25 years. Twelve of them were successfully validated with a confidence level of 95%. The models of asphalt in humid climate and concrete in dry climate need further analysis for their validation, considering more data collection in these climates.

- Hierarchies based on grouped functional classification were used: Primary Network for Express and Troncal classification; Secondary Network for Colector and Service classification; Local Network for local streets and passages. Individual functional classifications were not used because the UPCI evolution over time within them exhibited high variability with illogical patterns; however, these groups present logical patterns.

- Additionally, a comparative analysis was performed between the real equivalent axles demanding the sections and the equivalent axles admitted by their structures. Results of this analysis showed two different scenarios for Mediterranean climate network for asphalt and concrete pavements: (1) sections where the traffic demand maintains within the range of the structure capacity, and; (2) sections where the traffic demand exceeds the structure capacity. This analysis was also considered for performance models calibration. In the analysis of dry climate for asphalt pavements and humid climate for concrete pavements, not enough information was available to make this analysis possible.

- Models for Asphalt Pavement in Mediterranean Climate: Primary Network presents a consistent deterioration with the design of 20 years; Secondary Network shows more rapid deterioration than expected, apparently because the streets within this classification could be sub dimensioned for the real demand, and; Local network presents a low deterioration rate, probably due to over dimensioned of the streets. Considering the models resulted from the analysis of the design, when the traffic demand remains within the structural capacity of the pavement, UPCI deterioration over time is smoothed; however, when the traffic demand exceeds the structural capacity the deterioration over time is steeper lasting 9 years less than the first case. These performance models are recommended to use when information about traffic and structure is available. On the contrary, the models developed based on the hierarchy networks are recommended.

- Models for Asphalt in Dry and Humid Climate: Models for humid climate presents higher deterioration rate than model for dry climate. However, both models present a shorter service life than their design. This result is coherent with the observations of pavement condition in the field.

- Models for Concrete Pavement in Mediterranean Climate: Primary and Secondary networks show similar performance with a service life of 25 and 21 years, and; Local network presents a low deterioration rate, probably due to over dimensioned of the streets similar to asphalt pavements for this network. Considering the models resulted from the analysis of the design, the deterioration trend does not present big differences within the two conditions analyzed. This phenomenon can be explained by the fact that when traffic demands exceeds structural capacity for concrete pavements the difference is not very extreme as occurs in the case of asphalt pavements. Therefore, for concrete pavements is recommend the use of the models calibrated based on the hierarchy networks.

- Models for Concrete in Dry and Humid Climate: Both cases present a long service life; however, on the contrary of what is expected, the dry climate presents a deterioration more accelerated than humid climate between UPCI 8.5 to 4. This behavior is probably a consequence of differences in construction standards and maintenance policies, noticed in interviews carried out with agencies of both regions. This result is coherent with the observations of pavement condition in the field.

- Based on performance models obtained the following conclusions are made about the impacts of climate, traffic and structure: The relation between the traffic demand and the structural capacity has high impact in asphalt pavements deterioration, but low impact in concrete pavements; the climate presents low impact in asphalt pavements comparing global models for Mediterranean and dry climates; however, high impact in concrete pavements. In this latter behavior not only the climate effect is impacting but the construction standards and maintenance policies difference, noticed in interviews carried out with agencies of both regions.

- These curves may be easily adopted and adapted to different conditions, considering the extensive climate range application, type of pavements and the simplicity and cost-effectiveness of the UPCI evaluation.

3. **Recommend maintenance standards for the implementation of calibrated models in a management system**

- Suitable maintenance standards for urban pavement based on the urban pavement condition index and their performance models are recommended for asphalt and concrete pavements. Three different standards are proposed for primary, secondary and local networks.

- The definition of these standards was performed considering the information collected in the-state-of-the-and-the practice-review as well as the data collected during field evaluation of section maintained during the research time frame.

- The main difference with existing standards is that considers maintenance actions feasible to be applied in urban conditions. In addition, maintenance actions environmentally friendly are considered, such as pavement recycle.

9.1 Recommendations

Recommendations for the use and calibration of the tools developed in this research are the following:

Urban Pavement Condition Evaluation

- It is recommended that, in the case of application of the developed equations, agencies should consider the advantages and limitations of assessing the network manually or automatically.

- It is highly recommended the validation of UPCI equations when applying in pavements with different climates conditions due to the distresses may differ from the ones analyzed in this research. The process of validation to follow is the same as the presented for validation of UPCI equations in Section 6.2.

Performance Models

- The calibration over time of the developed curves is recommended to capture the performance of urban pavement during a larger period of time. The data collected during the time frame of this research gave a starting point of the models but future calibrations would improve the estimation of the deterioration trend.

- It is highly recommended the validation of performance models when applying to networks with different characteristics of pavement design and climate conditions.

P&M&R Standards

- The standards must be calibrated over time so the ranges of application, the effects in the UPCI and the maximum UPCI reachable for those P&M&R actions that are not currently use in urban pavement conditions can be better estimated.
- It is recommended the adjustment of maintenance standards to local conditions.

9.2 Thesis Main Contributions

The main scientific contributions from this research are the calibrated tools that facilitate the better understanding of urban pavements deterioration and maintenance:

- Urban Pavement Condition Index that reliably represents the combined effect of urban pavement distresses and delivers a global pavement condition for network analysis.
- Urban Pavement Performance Models for different climates, traffic and structures, that effectively predicted the deterioration of urban pavements over time, allowing the development of life cycle analysis for network management.

The main contributions to the state-of-the-practice are:

- The framework proposed that helps to integrate tools for sustainable management of urban networks
- The Condition Evaluation Guidelines for urban pavements
- The adaptability of performance models to different scenarios

9.3 Future Research and Developments

Topics for future research and developments were identified from the results of this research:

- It is recommended further analysis for the calibration of UPCI considering automated data collected for concrete pavements. Furthermore, calibration of UPCI for interlocking and cobblestone pavements would extend the use of the evaluation condition methodology.
- Re calibration of the UPCI models calibrated in this research using a sample with a higher power.
- Sensitivity analysis of UPCI models, including different ranges of distresses and coefficients of severity.
- Future studies are recommended to validate the models in the following cases:
    a. In the ranges with no data available in this research, for example lower values of UPCI in the cases of local network and Traffic Demand > Structural Capacity for asphalt pavements and almost all the case but Traffic Demand ≤ Structural Capacity for concrete pavements.
    b. In the cases where a few data was available for validation, for example Primary Network and Traffic Demand > Structural Capacity for asphalt pavements, and Traffic Demand > Structural Capacity for concrete pavements.

- Validation of the performance models calibrated for asphalt pavement in humid climate and concrete pavement in dry climate.
- Validation of performance models for asphalt and concrete pavements in different climates from the obtained in this research.
- Development of performance models for composite pavements of asphalt overlays over concrete pavements, concrete overlays over asphalt and concrete pavements, interlocking, and cobblestones pavements. With this, the scope of application of these tools for urban pavements would be extended broadly to other scenarios.
- Analysis the performance models considering the heterogeneity of traffic loads and the age of pavements, challenging information to obtain for urban pavements.
- Development of phone or tablet application for manual data collection in field evaluation. This application will improve the time frame for data processing, and the UPCI could be automated obtained. This tool would also facilitate the data collection over time if the data of last year's evaluations remains in the application for next evaluations.
- Development of performance models considering the different maintenance actions applied during the life cycle of pavements. This study would involve a long period of time for its development but could improve considerably the estimation of maintenance action effects in the life cycle analysis.
- Based on the difficulty faced to obtain inventory data of urban pavements from local agencies, it would be interesting the development of a methodology that facilitates inventory data collection from urban pavement projects and maintenance treatments history.

Appendix A

Windshield Evaluation Sheets

Asphalt Pavement - Windshield Evaluation

Street/Avenue:

From:

To:

Comuna: Lenght:

Traffic Direction: Lanes:

Survey date: Evaluator:

Asphalt Distresses		**Severity**			**Density**		
		Low	Moderate	High	Low	Frequent	Extended
Cracking	Fatigue/Alligator Cracking						
	Block Cracking						
	Edge Cracking						
	Wheel Path Longitudinal						
	Non-Wheel Path Longitudinal						
	Reflection Cracking						
	Transverse Cracking						
Patch and Potholes	Patch Deterioration						
	Potholes						
Surface Deformat.	Rutting						
	Shoving						
Surface Defects	Bleeding						
	Ravelling						
	Polished Aggregate						
Others	Curb deterioration						
	Water Bleeding and pumping						
	Manholes and catchbasins						

Observations

Concrete Pavement Evaluation

Street/Avenue:

From:

To:

Comuna: Lenght:

Traffic Direction: Lanes:

Survey date: Evaluator:

Concrete Distresses		Severity			Density		
		Low	Moderate	High	Low	Frequent	Extended
Cracking	Corner Breaks						
	Durability Cracking (D)						
	Longitudinal Cracking						
	Transverse Cracking						
	Oblicous Cracking						
Surface Deformat.	Faulting						
	Slab warping						
Surface Defects	Map Cracking						
	Scaling						
	Polished Aggregate						
	Popouts						
Joint Deficiencies	Transverse Joint Seal Damage						
	Longitudinal Joint Seal Damage						
	Spalling of longitudinal joints						
	Spalling of transverse joints						
	Blowups						
Others	Curb deterioration						
	Patch Deterioration						
	Water Bleeding and pumping						
	Manholes and catchbasins						

Observations

Appendix B
Distress Evaluation Guidelines

1. INTRODUCCIÓN

El principal objetivo del proyecto FONDEF D09I1018 “Investigación y Desarrollo de Soluciones para la Gestión de Pavimentos Urbanos en Chile”, es desarrollar herramientas para resolver los principales problemas institucionales, técnicos y económicos que se presentan en las instituciones a cargo de la gestión de pavimentos urbanos en Chile.

Este proyecto es desarrollado por la Pontificia Universidad Católica de Chile, en asociación con el Ministerio de Vivienda y Urbanismo (MINVU), el Gobierno Regional Metropolitano (GORE) y las Municipalidades de Santiago y Macul. El mismo está financiado por Fondef – Conicyt y todas las instituciones asociadas. Además, se cuenta con la asesoría externa de la Profesora Susan Tighe, directora del Centre for Pavement and Transportation Technology (CPATT) de la Universidad de Waterloo, Canadá.

El presente documento se enfoca en la Metodología de Evaluación de la Condición de Pavimentos Urbanos, considerando dos tipos de pavimentos, asfaltos y hormigones.

La Metodología de Evaluación Técnica está compuesta de cuatro actividades principales:

1. Desarrollo del Índice de Condición de Pavimentos Urbanos (ICPU). El ICPU es un índice combinado que representará el estado global de una sección de pavimento para analizarlo a nivel de red.

2. Elección de la Metodología de Evaluación de Deterioros, que presentará cómo se recolectarán los datos de los deterioros en cada tipo de pavimento a evaluar.

3. Definición del Muestreo, que indicará cuándo y cuánto se deberán evaluar los pavimentos.

4. Definición de la Jerarquía, que presentará dónde se deberá evaluar, en qué tipo de vías y qué tipo evaluaciones.

En este documento se presentan los puntos 2 y 3. Los documentos correspondientes a los puntos 1 y 4 fueron entregados en documentos técnicos separados.

2. MUESTRO DE EVALUACIÓN

Una unidad muestral es una sección de pavimento definida para ser evaluada. El tamaño de unidad muestral definido para cada tipo de pavimento es el siguiente:

- Asfaltos: Ancho de pista x 50 m de largo, subdividido en segmentos de 10 m
- Hormigones: Ancho de pista x 10 losas, donde cada losa es un segmento

Estas unidades muestrales se toman en la mitad de cada cuadra a ser evaluada.

La selección de cuadras a ser evaluadas se realiza en base a la jerarquía de las calles a evaluar:

- Red Primaria: Cada 2 años, 100%
- Red Intermedia: Cada 4 años, 100%
- Red Local: Cada 4 años, en tramos representativos condición observada en terreno. Se toma la cuadra que sea representativa del tramo homogéneo.

Los datos obtenidos por unidad muestral son los siguientes:

- Deterioros: superficiales, ahuellamiento y rugosidad.
- Datos de inventario: Referencias, ubicación GPS, largo y ancho, sentido del tráfico.

3. DETERIOROS A EVALUAR EN PAVIMENTOS ASFÁLTICOS

A continuación se describe brevemente cada tipo de deterioro que se deben evaluar en pavimentos asfálticos en zonas urbanas (DICTUC, 2006) (De Solminiac, 2001) (FHWA, 2003):

3.1 Grietas de Fatiga

Son grietas interconectadas en forma de piel de cocodrilo, que se asocian con la capacidad estructural del pavimento.. Se presenta principalmente en la huella, causadas por la fatiga de la carpeta asfáltica, debido a la acción repetida de las cargas de tránsito.

- Baja: área de grietas con poco o nada de interconexión; las mismas no se encuentran desprendidas o selladas; no se percibe bombeo de agua.

- Moderada: área de grietas interconectadas formando un patrón; las grietas se encuentran ligeramente desprendidas; pueden estar selladas; no se percibe bombeo de agua.
- Alta: área de grietas interconectadas formando un patrón con desintegración moderada o severa; los pequeños trozos de pavimento movidos; las grietas pueden estar sellasdas; no se percibe bombeo de agua.

Figura 9-1. Grietas de Fatiga de Alta Severidad

3.2 Grieta de Reflexión

Grietas presentes en recapados asfálticos, donde se encuentras las juntas del pavimento de hormigón subyacente.

- Baja: Promedio de ancho de grietas ≤ 6mm; o selladas con el sello en buen estado y con ancho que no puede ser definido.
- Moderada: Promedio de ancho de grietas > 6mm y ≤19mm; o grietas con ancho promedio ≤19mm y grietas adjacentes de baja severidad.
- Alta: Promedio de ancho de grietas > 19mm; o grietas con ancho promedio ≤19mm y grietas adjacentes de moderada o alta severidad.

3.3 Grieta Transversal

Grietas perpendiculares al sentido del tráfico.

- Baja: Promedio de ancho de grietas ≤ 6mm; o selladas con el sello en buen estado y con ancho que no puede ser definido.

- Moderada: Promedio de ancho de grietas > 6mm y ≤19mm; o grietas con ancho promedio ≤19mm y grietas adjacentes de baja severidad.
- Alta: Promedio de ancho de grietas > 19mm; o grietas con ancho promedio ≤19mm y grietas adjacentes de moderada o alta severidad.

Figura 9-2. Grietas de transversal de baja severidad

3.4 Ahuellamiento

Depresiones en la sección transversal del pavimento que se presentan en las huellas. Deterioro relacionado con la capacidad estructural del pavimento.

3.5 Baches

Desprendimiento y pérdida localizada de material que conforma la superficie de rodadura, con una dimensión mayor a 150 mm.

- Baja: < 25 mm de profundidad
- Moderada: ≥25mm y < 50 mm de profundidad
- Alta:>50 mm de profundidad

3.6 Parche Deteriorado

Parte de la superficie de rodado, mayor a 0,1 m^2, que fue removida y reemplazada, o material adicional que fue colocado en el pavimento durante su vída de servicio.

- Baja: El parche tiene deterioros de baja severidad, oahuellamiento ≤6mm, sin evidencia de bombeo.
- Moderada: El parche tiene deterioros de moderada severidad, o ahuellamiento >6mm y ≤12mm, sin evidencia de bombeo.
- Alta: El parche tiene deterioros de alta severidad, o ahuellamiento >12mm, o material adicional colocado, o puede tener evidencia de bombeo.

3.7 Rugosidad

Irregularidades en la superficie del pavimento, que afectan la calidad de rodado, seguridad y costos de operación de los vehículos.

4. DETERIOROS A EVALUAR EN PAVIMENTOS DE HORMIGÓN

A continuación se describe brevemente cada tipo de deterioro que se deben evaluar en pavimentos de hormigón en zonas urbanas (DICTUC, 2006) (De Solminiac, 2001) (FHWA, 2003):

4.1 Grieta de Esquina

Parte de la esquina de la losa separada por una grieta, que intersecta las juntas longitudinal y tranversal en un ángulo de 45°, con una longitud que varía entre 0,3m y la mitad del ancho de la losa.

- Baja: Grietas con desconche en menos el 10% de su longitud; sin presencia de escalonamiento; y la esquina de la losa no está partida en 2 o más piezas; sin pérdida de material o parche.
- Moderada: Grietas con desconche en más el 10% de su longitud; con escalonamiento <13 mm; y la esquina de la losa no está partida en 2 o más piezas; sin pérdida de material o parche.
- Alta: Grietas con desconche en más el 10% de su longitud; con escalonamiento > 13mm; o la esquina de la losa está partida en 2 o más piezas; o con pérdida de material o parche.

Figura 9-3. Grieta Esquina de Alta Severidad

4.2 Grieta Longitudinal

Grietas paralelas al sentido del tráfico.

- Baja: Ancho promedio de grietas < 3mm, sin desconche o ahuellamiento; o selladas con el sello en buen estado y con ancho que no puede ser definido.
- Moderada: Ancho promedio de ancho de grietas ≥ 3mm y <13mm, con desconche < 75mm o ahuellamiento< 13 mm.
- Alta: Ancho promedio de grietas ≥ 13mm, con desconche ≥ 75mm o ahuellamiento ≥ 13 mm.

4.3 Grieta Transversal

Grietas perpendiculares al sentido del tráfico.

- Baja: Ancho promedio de grietas < 3mm, sin desconche o ahuellamiento; o selladas con el sello en buen estado y con ancho que no puede ser definido.
- Moderada: Ancho promedio de ancho de grietas ≥ 3mm y <6mm, con desconche < 75mm o ahuellamiento< 6 mm.
- Alta: Ancho promedio de grietas ≥ 6mm, con desconche ≥ 75mm o ahuellamiento ≥ 6 mm.

Figura 9-4. Grieta transversal de alta severidad. Pavimento de Hormigón

4.4 Grieta Oblicua

Esta grieta se extiende uniendo la junta transversal con la junta longitudinal o unión berma-losa. Se asocia a fatiga, iniciándose y terminando en ángulo recto dentro del tercio central del borde transversal o longitudinal de la losa

- Baja: Ancho promedio < 10mm.
- Moderada: Ancho promedio ≥ 10 mm y < 100 mm.
- Alta: Ancho promedio > 100 mm.

4.5 Deterioro de Sello de Junta

Cualquier daño en la junta que permita el ingreso de material incompresible o agua desde la superficie hacia las capas inferiores del pavimento.

- Baja: Deterioro del sello de la junta transversal < 10% de la longitud de la junta.
- Moderada: Deterioro del sello de la junta transversal ≥ 10% y ≤50% de la longitud de la junta.
- Alta: Deterioro del sello de la junta transversal > 10% de la longitud de la junta.

Figura 9-5. Deterioro de Sello de Junta de baja severidad

4.6 Desconche de Junta Longitudinal y Transversal

Grietas o fisuras entre los bordes de las losas y una distancia de 0,3m desde la junta.

- Baja: Desconche < 75 mm de ancho, con pérdida de material; o desconches sin pérdida de material.
- Moderada: Desconche ≥75 mm y ≤ 150 mm de ancho, con pérdida de material.
- Alta: Desconche >150 mm, con pérdida de material; o partido en dos o más piezas.

Figura 9-6. Desconche de Junta de Alta Severidad

4.7 Escalonamiento

Diferencia en altura de las losas a lo largo de la junta transversal.

4.8 Parche Deteriorado

Parte de la superficie de rodado, mayor a 0,1 m^2, que fue removida y reemplazada, o material adicional que fue colocado en el pavimento durante su vída de servicio.

Figura 9-7. Parche Deteriorado de Severidad Media

4.9 Rugosidad

Irregularidades en la superficie del pavimento, que afectan la calidad de rodado, seguridad y costos de operación de los vehículos.

5. REFERENCIAS

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6. AGRADECIMIENTOS

El equipo del Proyecto agradece la colaboración de las siguientes instituciones que apoyaron en el Desarrollo del ICPU Manual y Automático:

- FONDEF – CONICYT
- MINVU & SERVIU Metropolitano
- Gobierno Regional Metropolitanos de Santiago
- Ilustre Municipalidad de Macul
- Ilustre Municipalidad de Santiago
- Dirección Nacional de Vialidad - Ministerio de Obras Públicas de Chile
- CPPAT – University of Waterloo
- Pontificia Universidad Católica de Chile

7. ANEXOS

Anexo 1. Planillas de Evaluación Pavimentos Asfálticos

Planilla de Evaluación de Pavimentos Asfálticos. Proyecto Fondef D09I1018

Hoja de

Calle/Avenida

Fecha

Unidad Muestral

Inicio

Dirección

Pista N°

Fin

Ancho de Pista

Evaluador

	Grietas												**Baches*** **			**Parche Deteriorado (m^2)***									**Ahuellamiento (mm)********
	Piel de Cocodrilo (m^2)*						**Transversal (m)****			**De reflexión (m)****															
	Baja		Media		Alta		Baja	Media	Alta	Baja	Media	Alta	ancho (m)	largo (m)	Prof. (mm)	Baja			Media			Alta			Mean Depth
Segmento (m)	ancho	largo	ancho	largo	ancho	largo										Cant.	ancho	largo	Cant.	ancho	largo	Cant.	ancho	largo	
0 - 10																									
10 - 20																									
20 - 30																									
30 - 40																									
40 - 50																									
50	0		0		0		0	0	0	0	0	0	0			0			0			0			
% Deter.																									

Fotos:

Observaciones:

Anexo 2. Planillas de Evaluación Pavimentos de Hormigón

Planilla de Evaluación de Pavimentos Hormigón. Proyecto Fondef D09I1018 Hoja de

Calle/Avenida Fecha

Unidad Muestral Inicio Ancho de Losa Dirección

Pista N° Fin Ancho de Pista Evaluador

Losa		**Grietas**												**Daño Sellos de las Juntas**			**Escalonamiento**		**Parches Deteriorados**									**IRI**
		De Esquina (m)			**Longitudinal (m)**			**Transversal (m)**			**Oblicua**																	
																			Baja			Media(< 6mm E)			Alta (> 6mm E)			
Longitud	N°	Baja <10% L	Media >10 %L < 13mm E	Alta >10 %L > 13mm E	Baja <3 mm	Media >3 mm <13mm	Alta >13mm	Baja <3 mm	Media >3 mm, <6mm	Alta <6mm	Baja < 10 mm	Media >10 mm <100mm	Alta > 100 mm	Baja	Media	Alta	Profundidad (mm)		Cant.	ancho	largo	Cant.	ancho	largo	Cant.	ancho	largo	
	1																											
	2																											
	3																											
	4																											
	5																											
	6																											
	7																											
	8																											
	9																											
	10																											
Total		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		#¡DIV/0!	0			0			0			
% Deterioros																												

Observaciones:

Appendix C

Analysis of Expert Evaluations

Asphalt Pavements

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	E1	4.8864	44	2.01409	.30364
	E2	4.9091	44	1.76290	.26577
Pair 2	E1	4.8864	44	2.01409	.30364
	E3	5.3636	44	2.05835	.31031
Pair 3	E1	4.8864	44	2.01409	.30364
	E4	5.8864	44	2.18042	.32871
Pair 4	E2	4.9091	44	1.76290	.26577
	E3	5.3636	44	2.05835	.31031
Pair 5	E2	4.9091	44	1.76290	.26577
	E4	5.8864	44	2.18042	.32871
Pair 6	E3	5.3636	44	2.05835	.31031
	E4	5.8864	44	2.18042	.32871

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	E1 - E2	-.02273	1.17114	.17656	-.37879	.33333	-.129	43	.898
Pair 2	E1 - E3	-.47727	1.15111	.17354	-.82724	-.12730	-2.750	43	.009
Pair 3	E1 - E4	-1.00000	1.12063	.16894	-1.34070	-.65930	-5.919	43	.000
Pair 4	E2 - E3	-.45455	1.53190	.23094	-.92029	.01120	-1.968	43	.056
Pair 5	E2 - E4	-.97727	1.37229	.20688	-1.39449	-.56006	-4.724	43	.000
Pair 6	E3 - E4	-.52273	1.32048	.19907	-.92419	-.12127	-2.626	43	.012

Concrete Pavements

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	E1	5.26	43	1.663	.254
	E2	6.21	43	1.424	.217
Pair 2	E1	5.26	43	1.663	.254
	E3	5.67	43	1.742	.266
Pair 3	E1	5.26	43	1.663	.254
	E4	4.60	43	1.050	.160
Pair 4	E1	5.26	43	1.663	.254
	E5	6.14	43	1.390	.212
Pair 5	E2	6.21	43	1.424	.217
	E3	5.67	43	1.742	.266
Pair 6	E2	6.21	43	1.424	.217
	E4	4.60	43	1.050	.160
Pair 7	E2	6.21	43	1.424	.217
	E5	6.14	43	1.390	.212
Pair 8	E3	5.67	43	1.742	.266
	E4	4.60	43	1.050	.160
Pair 9	E3	5.67	43	1.742	.266
	E5	6.14	43	1.390	.212
Pair 10	E4	4.60	43	1.050	.160
	E5	6.14	43	1.390	.212

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	E1 - E2	-.953	.872	.133	-1.222	-.685	-7.174	42	.000
Pair 2	E1 - E3	-.419	1.418	.216	-.855	.018	-1.936	42	.060
Pair 3	E1 - E4	.651	1.446	.220	.206	1.096	2.954	42	.005
Pair 4	E1 - E5	-.884	1.159	.177	-1.240	-.527	-5.000	42	.000
Pair 5	E2 - E3	.535	1.470	.224	.083	.987	2.387	42	.022
Pair 6	E2 - E4	1.605	1.294	.197	1.207	2.003	8.134	42	.000
Pair 7	E2 - E5	.070	.799	.122	-.176	.316	.573	42	.570
Pair 8	E3 - E4	1.070	1.805	.275	.514	1.625	3.887	42	.000
Pair 9	E3 - E5	-.465	1.386	.211	-.892	-.039	-2.200	42	.033
Pair 10	E4 - E5	-1.535	1.420	.217	-1.972	-1.098	-7.088	42	.000

Interlocking Pavements

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	E1	5.6591	44	1.23784	.18661
	E2	5.7045	44	1.77292	.26728
Pair 2	E1	5.6591	44	1.23784	.18661
	E3	4.5682	44	.69542	.10484
Pair 3	E1	5.6591	44	1.23784	.18661
	E4	5.3409	44	1.65576	.24962
Pair 4	E2	5.7045	44	1.77292	.26728
	E3	4.5682	44	.69542	.10484
Pair 5	E2	5.7045	44	1.77292	.26728
	E4	5.3409	44	1.65576	.24962
Pair 6	E3	4.5682	44	.69542	.10484
	E4	5.3409	44	1.65576	.24962

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	E1 - E2	-.04545	1.11969	.16880	-.38587	.29496	-.269	43	.789
Pair 2	E1 - E3	1.09091	1.15775	.17454	.73892	1.44290	6.250	43	.000
Pair 3	E1 - E4	.31818	.93443	.14087	.03409	.60227	2.259	43	.029
Pair 4	E2 - E3	1.13636	1.59346	.24022	.65191	1.62082	4.730	43	.000
Pair 5	E2 - E4	.36364	1.31345	.19801	-.03569	.76296	1.836	43	.073
Pair 6	E3 - E4	-.77273	1.50756	.22727	-1.23107	-.31439	-3.400	43	.001

Appendix D

Data Collected for Development and Validation of UPCI

Asphalt Pavements

Section	Cracking					Shoving %	Bleeding %	Potholes %	Raveling %	Polished Aggregate %	Deteriorated Patch %	Manholes and Catchbasins N°	Rutting mm	$UPCI_{OBS}$
	Fatigue %	Long Wheel Path %	Long No Wheel Path %	Transversal %	Reflection %									
1	22.33	0.00	0.00	13.53	0.00	0.00	0.10	0.00	0.82	0.00	2.37	0.00	4.40	6.00
2	17.45	0.00	0.00	10.72	0.00	0.00	0.00	0.04	0.00	0.00	0.94	2.00	3.40	6.00
3	53.07	0.00	0.00	3.24	0.00	0.00	0.00	0.30	0.40	0.00	1.95	0.00	2.67	4.00
5	88.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	5.40	5.00
6	44.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	5.67
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	2.20	8.67
11	8.93	0.00	8.41	9.86	0.00	0.00	0.00	0.00	12.09	0.00	9.35	0.00	2.20	6.00
12	0.10	0.00	4.06	2.96	0.00	0.00	0.00	0.00	7.22	0.00	9.94	0.00	1.00	6.00
13	47.32	4.30	2.48	7.04	0.00	0.00	0.00	0.00	6.87	0.00	57.44	0.00	6.50	4.33
14	41.16	0.00	8.32	18.65	0.00	0.00	0.00	0.00	3.74	0.00	32.48	2.50	5.20	4.00
15	59.21	0.00	5.19	18.87	0.00	0.00	0.00	0.00	7.43	0.00	39.19	4.00	8.50	4.00
17	180.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.69	0.00	4.00	2.33
19	0.00	0.00	0.00	0.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.13	8.67
22	67.68	0.00	0.00	7.20	0.00	0.00	0.00	0.12	14.35	0.00	12.80	0.00	2.40	4.00
25	6.97	0.00	0.00	1.26	0.00	0.00	0.00	0.00	7.89	0.00	7.35	0.00	1.00	6.33
26	36.46	0.21	6.00	0.00	0.00	0.00	2.42	0.00	0.00	7.89	5.66	0.50	0.50	6.33
27	32.96	0.00	0.00	12.80	0.00	0.00	0.00	0.00	0.00	80.00	0.59	0.00	0.80	6.00
28	120.61	0.00	0.00	8.48	0.00	0.00	0.00	1.16	0.00	0.00	0.88	0.00	1.80	4.33
29	5.53	0.00	0.00	3.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.67
30	3.80	0.00	1.24	10.59	3.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	7.33
31	64.16	0.00	1.32	0.00	0.00	0.00	0.00	0.07	0.00	0.00	13.83	0.00	2.40	5.67
32	61.55	0.00	1.53	2.16	4.82	0.00	0.00	0.00	0.00	0.00	0.00	0.50	2.00	5.67
33	100.68	0.00	0.00	7.30	0.00	0.00	0.00	0.71	0.00	0.00	19.09	0.00	23.80	2.00
34	57.04	0.00	7.24	27.09	0.00	0.00	0.00	0.00	0.00	16.47	14.20	0.00	6.00	3.33
36	109.09	0.00	4.36	19.03	0.00	0.00	0.00	2.25	0.58	0.00	18.72	0.00	2.00	2.67
38	0.06	0.00	0.00	4.13	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	8.67

Section	Cracking					Shoving %	Bleeding %	Potholes %	Raveling %	Polished Aggregate %	Deteriorated Patch %	Manholes and Catchbasins N°	Rutting mm	$UPCI_{OBS}$
	Fatigue %	Long Wheel Path %	Long No Wheel Path %	Transversal %	Reflection %									
39	0.43	0.00	8.37	1.07	0.00	0.00	0.21	0.00	10.00	0.00	0.00	2.00	1.00	6.33
43	0.00	0.00	2.62	2.46	64.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	1.00	4.67
44	5.92	0.00	0.00	30.40	7.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	5.67
46	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	9.00
48	28.51	0.00	0.00	4.53	61.38	0.00	11.40	0.00	0.00	12.80	0.00	0.00	2.00	4.67
51	0.00	0.00	0.00	3.43	33.71	14.29	28.57	0.00	30.29	0.00	0.00	0.50	20.00	5.67
52	0.00	0.00	0.00	0.20	32.27	0.00	66.67	0.00	20.00	0.00	0.00	0.00	28.25	5.67
54	0.00	0.00	25.89	12.00	22.00	0.00	0.00	0.00	14.29	0.00	0.00	0.00	1.00	6.67
56	0.62	0.00	36.69	19.40	20.00	0.00	0.00	0.00	0.00	14.29	0.00	0.00	15.70	5.00
58	0.00	0.00	0.00	6.17	0.00	0.00	0.83	0.00	14.29	0.00	0.00	0.50	1.00	7.00
59	0.76	0.00	0.23	2.51	29.94	0.00	0.00	0.00	22.86	0.00	0.00	4.00	1.00	5.67
60	26.34	0.00	42.29	8.80	65.14	0.00	0.00	0.33	0.00	0.00	0.00	0.00	2.00	4.33
4	107.88	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	41.18	0.00	0.00	3.67	4.33
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.67
18	8.96	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	1.10	8.33
21	137.20	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	68.60	55.73	0.00	1.60	1.67
23	19.73	0.00	0.00	7.71	0.00	0.00	0.00	0.00	0.00	5.71	26.91	0.00	17.80	4.67
24	23.32	0.00	18.51	22.55	0.00	0.00	0.00	0.00	0.00	0.00	7.85	0.00	2.40	6.00
35	56.77	0.00	13.94	38.53	0.00	0.00	0.00	0.00	0.05	15.68	4.66	0.00	16.00	3.33
37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.06	0.00	49.82	0.00	3.25	2.67
40	21.80	0.00	2.67	19.27	0.00	0.00	4.05	0.00	0.00	0.00	0.00	0.00	4.40	5.67
42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
45	26.73	0.00	0.00	37.23	26.74	0.00	0.00	0.00	23.43	0.00	0.00	0.00	5.60	5.00
47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10	9.00
49	12.67	0.00	6.67	11.73	27.80	0.00	16.00	0.16	0.00	26.67	0.00	1.00	8.00	3.67
53	0.00	0.00	0.00	0.93	12.47	0.80	76.67	0.00	0.00	2.67	0.00	2.00	26.40	5.33
55	0.00	0.00	6.74	5.23	21.46	0.00	0.00	0.00	21.14	0.00	0.00	0.00	1.00	6.67
57	0.00	0.00	10.54	20.00	24.00	0.00	0.00	0.00	0.17	14.42	0.00	0.00	1.60	5.67

▨ Validation Data

Concrete Pavements

Section	Cracking				Deteriorated Patch %	Faulting mm	Seal Damage %	$UPCI_{OBS}$
	Corner Break %	Longitudinal %	Transversal %	Oblique %				
61	7.00	2.00	10.00	7.00	0.00	3.00	42.00	7.00
62	5.00	0.00	31.00	7.00	0.00	4.00	42.00	4.00
63	0.00	23.00	25.00	5.00	0.00	3.00	26.00	5.00
66	0.00	0.00	0.00	0.00	0.00	0.00	47.00	10.00
67	0.00	1.00	5.00	0.00	0.00	2.00	16.00	8.00
68	0.00	4.00	8.00	2.00	0.00	4.00	60.00	6.00
69	2.00	16.00	20.00	0.00	0.00	2.00	56.00	6.00
70	0.00	0.00	7.00	0.00	0.00	3.00	113.00	8.00
71	0.00	0.00	19.00	0.00	0.00	0.00	100.00	7.00
75	0.00	3.00	18.00	0.00	0.00	1.00	32.00	8.00
76	0.00	1.00	7.00	1.00	6.00	2.00	21.00	8.00
77	0.00	0.00	2.00	0.00	1.00	3.00	35.00	8.00
80	0.00	1.00	0.00	0.00	0.00	7.00	26.00	9.00
81	1.00	0.00	0.00	0.00	0.00	3.00	22.00	9.00
82	0.00	1.00	0.00	0.00	0.00	3.00	18.00	8.00
83	0.00	0.00	2.00	0.00	0.00	2.00	31.00	8.00
84	0.00	0.00	1.00	0.00	0.00	3.00	31.00	8.00
85	1.00	2.00	0.00	8.00	0.00	2.00	54.00	7.00
86	4.00	70.00	12.00	3.00	2.00	5.00	36.00	6.00
88	2.00	0.00	0.00	0.00	0.00	0.00	55.00	10.00
89	0.00	28.00	10.00	0.00	0.00	6.00	46.00	6.00
90	3.00	42.00	21.00	0.00	0.00	4.00	53.00	5.00
91	0.00	2.00	16.00	2.00	0.00	5.00	51.00	8.00
92	0.00	0.00	16.00	0.00	0.00	1.00	53.00	8.00
93	1.00	72.00	23.00	0.00	0.00	4.00	40.00	4.00
94	0.00	61.00	5.00	0.00	0.00	4.00	28.00	4.00
95	0.00	12.00	5.00	1.00	0.00	3.00	95.00	6.00
96	0.00	6.00	0.00	0.00	0.00	2.00	60.00	8.00
97	0.00	0.00	151.00	0.00	46.00	3.00	75.00	2.00
98	0.00	0.00	144.00	56.00	38.00	1.00	19.00	2.00
99	2.00	68.00	20.00	1.00	0.00	4.00	61.00	4.00
100	0.00	59.00	20.00	1.00	0.00	4.00	52.00	6.00
101	2.00	52.00	33.00	6.00	1.00	5.00	26.00	5.00
102	0.00	21.00	48.00	1.00	2.00	5.00	16.00	4.00
103	1.00	26.00	17.00	0.00	0.00	1.00	67.00	6.00
104	1.00	4.00	8.00	0.00	0.00	2.00	53.00	6.00
105	0.00	3.00	7.00	0.00	0.00	2.00	25.00	8.00
107	1.00	17.00	74.00	1.00	0.00	5.00	55.00	4.00
108	0.00	3.00	8.00	2.00	30.00	5.00	45.00	4.00
109	0.00	0.00	1.00	0.00	0.00	7.00	24.00	9.00
112	0.00	11.00	28.00	1.00	5.00	4.00	39.00	8.00
113	0.00	15.00	52.00	1.00	0.00	9.00	62.00	4.00
114	1.00	17.00	51.00	6.00	3.00	8.00	72.00	3.00
115	2.00	25.00	40.00	2.00	1.00	4.00	55.00	5.00
116	2.00	16.00	55.00	1.00	5.00	6.00	53.00	4.00

Section	Cracking				Deteriorated Patch %	Faulting mm	Seal Damage %	$UPCI_{OBS}$
	Corner Break %	Longitudinal %	Transversal %	Oblique %				
119	6.00	12.00	12.00	1.00	8.00	5.00	58.00	4.00
121	2.00	31.00	37.00	1.00	0.00	5.00	58.00	6.00
122	2.00	27.00	42.00	1.00	2.00	6.00	60.00	6.00
123	1.00	6.00	29.00	0.00	0.00	5.00	52.00	6.00
124	2.00	55.00	64.00	0.00	16.00	8.00	44.00	3.00
125	1.00	6.00	146.00	2.00	4.00	9.00	63.00	2.00
126	0.00	26.00	66.00	52.00	1.00	6.00	22.00	3.00
128	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
129	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
130	0.00	3.00	7.00	0.00	1.00	8.00	3.00	9.00
135	0.00	28.00	21.00	2.00	11.00	8.00	10.00	3.00
136	0.00	0.00	108.00	0.00	52.00	3.00	20.00	2.00
137	0.00	3.00	142.00	0.00	24.00	8.00	22.00	2.00
146	1.00	76.00	69.00	0.00	1.00	6.00	73.00	2.00
147	3.00	68.00	66.00	4.00	0.00	5.00	66.00	2.00
152	0.00	21.00	30.00	0.00	9.00	7.00	44.00	4.00
1	0.15	1.57	4.64	3.98	0.59	4.80	170.55	6.50
2	12.01	3.25	15.05	4.56	0.00	5.30	169.98	3.25
3	0.14	0.39	4.92	13.99	2.48	7.70	168.41	5.00
4	0.00	0.00	0.00	6.75	0.00	5.10	169.58	5.75
5	0.00	36.95	17.67	5.19	6.83	8.20	11.98	5.25
6	0.00	39.78	85.59	7.19	0.31	4.80	35.43	5.00
7	0.00	14.14	25.05	0.53	3.35	4.40	3.40	4.75
8	0.00	27.37	42.59	0.00	0.04	7.50	0.00	3.75
9	0.69	0.22	13.06	0.56	8.80	5.00	63.68	5.50
10	0.31	0.05	6.87	0.00	1.70	6.60	61.52	5.50
11	0.00	0.54	0.00	0.00	0.00	7.50	94.33	6.00
12	0.00	0.00	0.00	0.89	0.01	4.10	94.28	6.00
13	0.00	0.00	0.00	0.00	0.00	5.40	0.00	5.00
14	0.00	0.00	0.00	0.00	0.00	5.20	102.35	5.00
15	0.00	0.00	0.99	0.00	0.00	4.70	100.90	6.75
16	0.00	0.00	0.00	0.00	0.00	3.50	79.26	6.75
17	0.00	0.96	3.33	0.00	0.00	5.90	60.00	6.50
18	0.00	2.48	0.00	0.00	0.00	3.10	0.00	6.50
19	0.00	0.00	6.81	0.00	0.00	3.60	90.55	5.75
20	0.00	0.00	5.07	0.00	0.00	2.70	67.66	6.25
21	0.00	0.98	0.00	0.00	0.00	4.50	174.16	6.50
22	0.00	0.00	0.00	0.00	0.00	0.40	108.76	8.50
23	0.00	2.33	7.19	0.00	0.00	3.70	171.28	6.50
24	0.00	0.00	0.00	0.00	0.00	5.40	114.29	5.00
25	0.37	6.01	0.00	0.00	0.00	6.80	77.52	4.50
26	0.00	13.73	5.68	3.79	0.00	4.50	105.76	5.50
27	2.14	10.94	3.50	0.00	0.00	2.80	105.71	5.25
28	0.44	0.00	9.21	0.00	0.00	3.00	297.67	6.00
29	0.30	0.74	23.01	0.00	0.00	2.20	297.89	5.75

Section	Cracking				Deteriorated Patch %	Faulting mm	Seal Damage %	UPCI$_{OBS}$
	Corner Break %	Longitudinal %	Transversal %	Oblique %				
30	0.00	0.32	0.00	0.00	0.00	3.50	125.69	6.50

▨ Validation Data

Interlocking Pavements

Section	Cracking and Seal Damage %	Potholes %	Deteriorated Patch %	UPCI$_{OBS}$
1	0.00	0.00	17.00	7.00
2	0.00	0.00	1.00	6.00
3	0.00	0.00	1.00	7.33
5	47.00	1.00	1.00	4.67
6	34.00	0.00	35.00	3.33
7	59.00	1.00	17.00	5.33
8	59.00	0.00	13.00	4.67
9	60.00	1.00	13.00	4.67
11	40.00	0.00	6.00	5.00
12	17.00	0.00	16.00	5.00
13	24.00	0.00	25.00	5.33
14	25.00	0.00	20.00	4.67
16	28.00	0.00	18.00	5.67
17	47.00	0.00	21.00	5.67
19	3.00	7.00	18.00	3.33
20	11.00	0.00	26.00	4.00
22	28.00	0.00	7.00	4.67
25	76.00	0.00	6.00	5.67
26	68.00	0.00	0.00	6.33
27	78.00	0.00	0.00	5.00
28	68.00	0.00	0.00	5.00
30	104.00	0.00	0.00	5.33
31	46.00	0.00	1.00	5.33
32	61.00	2.00	1.00	5.33
33	27.00	0.00	1.00	5.00
34	76.00	2.00	0.00	5.33
36	36.00	0.00	0.00	6.00
39	19.00	0.00	11.00	4.67
41	32.00	0.00	7.00	4.67
48	19.00	0.00	42.00	4.00
51	0.00	0.00	0.00	6.33
52	5.00	0.00	0.00	6.00
54	4.00	0.00	0.00	6.33
56	20.00	0.00	30.00	4.00
4	0.00	0.72	1.31	6.33
10	28.06	0.00	15.36	5.33
18	54.81	0.00	19.66	6.00
21	4.57	4.59	26.51	3.33
23	101.00	0.00	2.38	5.67
35	47.91	0.00	0.00	6.00
37	29.13	0.00	15.78	5.00
40	26.32	0.00	7.11	5.67
42	27.50	0.00	7.34	4.33
45	0.00	0.00	63.83	3.33

47	17.63	0.00	61.17	3.67
49	0.00	0.00	54.40	3.33
53	3.08	0.00	1.81	6.00
55	37.88	0.00	12.26	6.33
57	0.00	0.00	0.00	8.33

▨ Validation Data

Appendix E

Data Collected for Performance Models – Summary of lengths

Asphalt Pavements – Mediterranean Climate – Primary Network (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	19,654	2,336	-	-	-	-	-	-	-	21,990
8.99 - 8.00	-	1,645	2,146	-	-	-	-	-	-	3,791
7.99 - 7.00	-	-	-	1,025	1,155	-	-	-	-	2,180
6.99 - 6.00	-	-	-	311	712	-	311	-	-	1,334
5.99 - 5.00	-	-	-	-	1,424	322	-	-	-	1,746
4.99 - 4.00	-	-	-	-	-	-	-	-	-	-
3.99 - 3.00	-	-	-	-	-	-	-	-	536	536
2.99 - 2.00	-	-	-	-	-	-	-	763	763	1,526
1.99 - 1.00	-	-	-	-	-	-	-	-	-	-

Asphalt Pavements – Mediterranean Climate – Secondary Network (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	4,782	2,457	2,161	900	-	-	-	-	-	10,300
8.99 - 8.00	-	3,240	2,512	100	612	-	-	-	-	6,464
7.99 - 7.00	-	-	2,790	2,883	601	-	-	-	-	6,274
6.99 - 6.00	-	-	-	1,093	1,000	-	-	-	-	2,093
5.99 - 5.00	-	-	-	-	1,045	572	397	-	-	2,014
4.99 - 4.00	-	-	-	-	-	675	-	678	-	1,353
3.99 - 3.00	-	-	-	-	-	-	840	233	-	1,073
2.99 - 2.00	-	-	-	-	-	-	-	-	-	-
1.99 - 1.00	-	-	-	-	-	-	-	-	1,018	1,018

Asphalt Pavements – Mediterranean Climate – Local Network (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	948	1,088	606	-	-	-	-	-	-	2,642
8.99 - 8.00	-	1,066	-	-	-	-	-	-	-	1,066
7.99 - 7.00	-	-	3,494	-	-	-	-	-	-	3,494
6.99 - 6.00	-	-	-	2,054	190	1,129	-	-	-	3,373
5.99 - 5.00	-	-	-	-	190	-	-	-	-	190
4.99 - 4.00	-	-	-	-	-	1,903	231	-	-	2,134
3.99 - 3.00	-	-	-	-	-	-	-	399	-	399
2.99 - 2.00	-	-	-	-	-	-	-	399	587	986
1.99 - 1.00	-	-	-	-	-	-	-	-	359	359

Asphalt Pavements – Mediterranean Climate – Traffic Demand ≤ Structural Capacity (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	21,885	2,338	1,144	-	-	-	-	-	-	25,367
8.99 - 8.00	-	3,991	956	-	-	-	-	-	-	4,947
7.99 - 7.00	-	-	4,180	2,427	1,155	-	-	-	-	7,762
6.99 - 6.00	-	-	-	925	712	-	-	-	-	1,637
5.99 - 5.00	-	-	-	-	836	572	-	-	-	1,408
4.99 - 4.00	-	-	-	-	-	1,362	231	-	-	1,593
3.99 - 3.00	-	-	-	-	-	-	233	632	-	865
2.99 - 2.00	-	-	-	-	-	-	-	399	587	986
1.99 - 1.00	-	-	-	-	-	-	-	-	359	359

Asphalt Pavements – Mediterranean Climate – Traffic Demand > Structural Capacity (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	1,736	754	-	900	-	-	-	-	-	3,390
8.99 - 8.00	-	1,960	1,712	-	-	-	-	-	-	3,672
7.99 - 7.00	-	-	-	959	-	-	-	-	-	959
6.99 - 6.00	-	-	-	1,270	900	-	311	-	-	2,481
5.99 - 5.00	-	-	-	-	1,842	-	-	-	-	1,842
4.99 - 4.00	-	-	-	-	-	206	-	-	-	206
3.99 - 3.00	-	-	-	-	-	-	266	-	234	500
2.99 - 2.00	-	-	-	-	-	-	-	175	175	350
1.99 - 1.00	-	-	-	-	-	-	-	-	210	210

Concrete Pavements – Mediterranean Climate– Primary Network (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	3,769	569	586	-	-	-	-	-	-	4,924
8.99 - 8.00	-	2,762	2,097	-	-	-	-	-	-	4,859
7.99 - 7.00	-	-	3,738	2,107	-	387	-	-	-	6,232
6.99 - 6.00	-	-	-	1,785	1,048	231	-	-	-	3,064
5.99 - 5.00	-	-	-	-	1,820	570	-	-	-	2,390
4.99 - 4.00	-	-	-	-	-	849	671	-	-	1,520
3.99 - 3.00	-	-	-	-	-	-	671	-	-	671
2.99 - 2.00	-	-	-	-	-	-	-	-	-	-
1.99 - 1.00	-	-	-	-	-	-	-	-	180	180

Concrete Pavements – Mediterranean Climate– Secondary Network (meters)

Current Condition *i*	Future Condition *j*									Sum
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	592	3,004	643	-	-	-	-	-	-	4,239
8.99 - 8.00	-	5,426	2,678	-	-	-	-	-	-	8,104
7.99 - 7.00	-	-	2,330	4,711	640	559	-	-	-	8,240
6.99 - 6.00	-	-	-	6,263	606	632	-	-	-	7,501
5.99 - 5.00	-	-	-	-	3,372	4,832	565	-	-	8,769
4.99 - 4.00	-	-	-	-	-	10,331	1,364	-	-	11,695
3.99 - 3.00	-	-	-	-	-	-	565	985	-	1,550
2.99 - 2.00	-	-	-	-	-	-	-	-	-	-
1.99 - 1.00	-	-	-	-	-	-	-	-	180	180

Concrete Pavements – Mediterranean Climate– Local Network (meters)

Current Condition *i*	Future Condition *j*									Sum
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	921	-	-	-	-	-	-	-	-	921
8.99 - 8.00	-	4,139	983	464	-	-	-	-	-	5,586
7.99 - 7.00	-	-	2,484	501	793	-	-	-	-	3,778
6.99 - 6.00	-	-	-	1,849	1,697	192	-	-	-	3,738
5.99 - 5.00	-	-	-	-	6,004	-	-	-	-	6,004
4.99 - 4.00	-	-	-	-	-	589	399	-	-	988
3.99 - 3.00	-	-	-	-	-	-	571	519	-	1,090
2.99 - 2.00	-	-	-	-	-	-	-	1,721	367	2,088
1.99 - 1.00	-	-	-	-	-	-	-	-	180	180

Concrete Pavements – Mediterranean Climate – Traffic Demand ≤ Structural Capacity (meters)

Current Condition *i*	Future Condition *j*									Sum
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	5,282	2,699	1,229	-	-	-	-	-	-	9,210
8.99 - 8.00	-	11,724	5,061	464	-	-	-	-	-	17,249
7.99 - 7.00	-	-	7,005	6,449	734	559	-	-	-	14,747
6.99 - 6.00	-	-	-	6,553	2,605	1,055	-	-	-	10,213
5.99 - 5.00	-	-	-	-	9,941	5,402	565	-	-	15,908
4.99 - 4.00	-	-	-	-	-	8,505	1,763	-	-	10,268
3.99 - 3.00	-	-	-	-	-	-	1,136	1,504	-	2,640
2.99 - 2.00	-	-	-	-	-	-	-	1,721	367	2,088
1.99 - 1.00	-	-	-	-	-	-	-	-	367	367

Concrete Pavements – Mediterranean Climate – Traffic Demand > Structural Capacity (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	-	874	-	-	-	-	-	-	-	874
8.99 - 8.00	-	603	697	-	-	-	-	-	-	1,300
7.99 - 7.00	-	-	1,547	870	699	387	-	-	-	3,503
6.99 - 6.00	-	-	-	2,598	-	-	-	-	-	2,598
5.99 - 5.00	-	-	-	-	821	-	-	-	-	821
4.99 - 4.00	-	-	-	-	-	3,264	671	-	-	3,935
3.99 - 3.00	-	-	-	-	-	-	671	-	-	671
2.99 - 2.00	-	-	-	-	-	-	-	1,410	90	1,500
1.99 - 1.00	-	-	-	-	-	-	-	-	180	180

Asphalt Pavements – Dry Climate – Global (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	11,915	1,947	105	403	-	-	-	-	-	14,370
8.99 - 8.00	-	1,557	1,641	468	-	-	-	-	-	3,666
7.99 - 7.00	-	-	782	680	105	-	-	-	-	1,567
6.99 - 6.00	-	-	-	102	205	149	207	-	-	663
5.99 - 5.00	-	-	-	-	364	604	-	263	-	1,231
4.99 - 4.00	-	-	-	-	-	137	135	-	-	272
3.99 - 3.00	-	-	-	-	-	-	532	1,502	-	2,034
2.99 - 2.00	-	-	-	-	-	-	-	950	398	1,348
1.99 - 1.00	-	-	-	-	-	-	-	-	1,992	1,992

Concrete Pavements – Humid Climate– Global (meters)

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	1,057	330	-	-	-	-	-	-	-	1,387
8.99 - 8.00	-	1,203	163	-	-	-	-	-	-	1,366
7.99 - 7.00	-	-	970	218	145	-	-	-	-	1,333
6.99 - 6.00	-	-	-	502	273	-	-	-	-	775
5.99 - 5.00	-	-	-	-	863	836	315	-	-	2,014
4.99 - 4.00	-	-	-	-	-	696	807	-	-	1,503
3.99 - 3.00	-	-	-	-	-	-	433	308	-	741
2.99 - 2.00	-	-	-	-	-	-	-	640	370	1,010
1.99 - 1.00	-	-	-	-	-	-	-	-	136	136

Appendix F

Results of Regression Analysis for UPCI Calibration

Asphalt Pavement – Manual Data Collected

Descriptive Statistics

	Mean	Std. Deviation	N
ES_Promedio_sinE2	5.5526	1.70369	38
PieldeCocodrilo	34.008240	42.2251679	38
Trans_Reflexión	16.6543	19.70511	38
ParcheDeteriorado	6.749204	12.5298272	38
Ahuellamientomm	4.464254	6.5247050	38
Baches	.141668	.4201886	38

Correlations

		ES_Promedio_sinE2	PieldeCocodrilo	Trans_Reflexión	ParcheDeteriorado	Ahuellamientomm	Baches
Pearson Correlation	ES_Promedio_sinE2	1.000	-.723	-.243	-.466	-.334	-.446
	PieldeCocodrilo	-.723	1.000	-.249	.336	.066	.475
	Trans_Reflexión	-.243	-.249	1.000	-.148	.176	.071
	ParcheDeteriorado	-.466	.336	-.148	1.000	.156	.120
	Ahuellamientomm	-.334	.066	.176	.156	1.000	.019
	Baches	-.446	.475	.071	.120	.019	1.000
Sig. (1-tailed)	ES_Promedio_sinE2	.	.000	.071	.002	.020	.003
	PieldeCocodrilo	.000	.	.066	.020	.347	.001
	Trans_Reflexión	.071	.066	.	.187	.145	.336
	ParcheDeteriorado	.002	.020	.187	.	.175	.236
	Ahuellamientomm	.020	.347	.145	.175	.	.455
	Baches	.003	.001	.336	.236	.455	.
N	ES_Promedio_sinE2	38	38	38	38	38	38
	PieldeCocodrilo	38	38	38	38	38	38
	Trans_Reflexión	38	38	38	38	38	38
	ParcheDeteriorado	38	38	38	38	38	38
	Ahuellamientomm	38	38	38	38	38	38
	Baches	38	38	38	38	38	38

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Baches, Ahuellamientomm, Trans_Reflexión, ParcheDeteriorado, PieldeCocodrilo[b]	.	Enter

a. Dependent Variable: ES_Promedio_sinE2

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.902[a]	.814	.785	.79070

a. Predictors: (Constant), Baches, Ahuellamientomm, Trans_Reflexión, ParcheDeteriorado, PieldeCocodrilo

b. Dependent Variable: ES_Promedio_sinE2

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	87.388	5	17.478	27.955	.000[b]
	Residual	20.007	32	.625		
	Total	107.395	37			

a. Dependent Variable: ES_Promedio_sinE2

b. Predictors: (Constant), Baches, Ahuellamientomm, Trans_Reflexión, ParcheDeteriorado, PieldeCocodrilo

Coefficients[a]

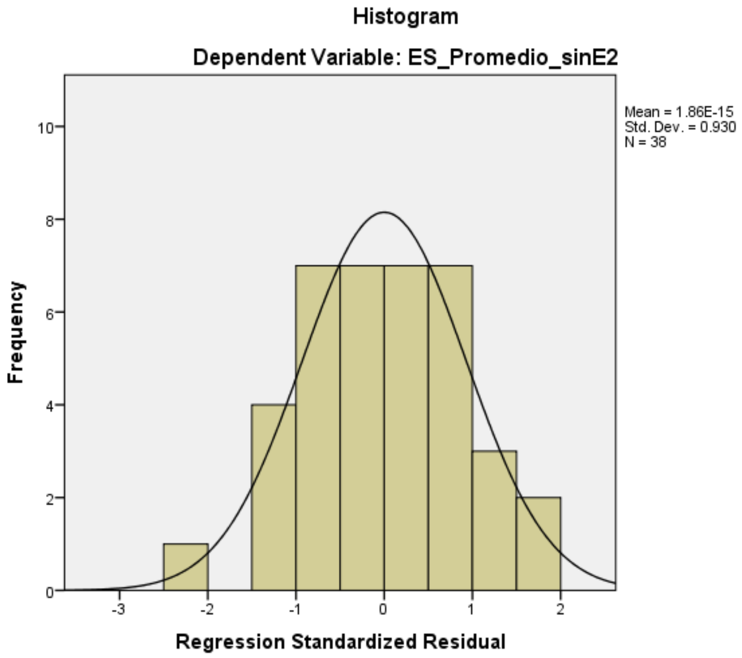
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.600	.230		33.052	.000
	PieldeCocodrilo	-.029	.004	-.710	-7.402	.000
	Trans_Reflexión	-.037	.007	-.424	-5.116	.000
	ParcheDeteriorado	-.035	.011	-.258	-3.139	.004
	Ahuellamientomm	-.045	.021	-.171	-2.162	.038
	Baches	-.180	.361	-.044	-.499	.621

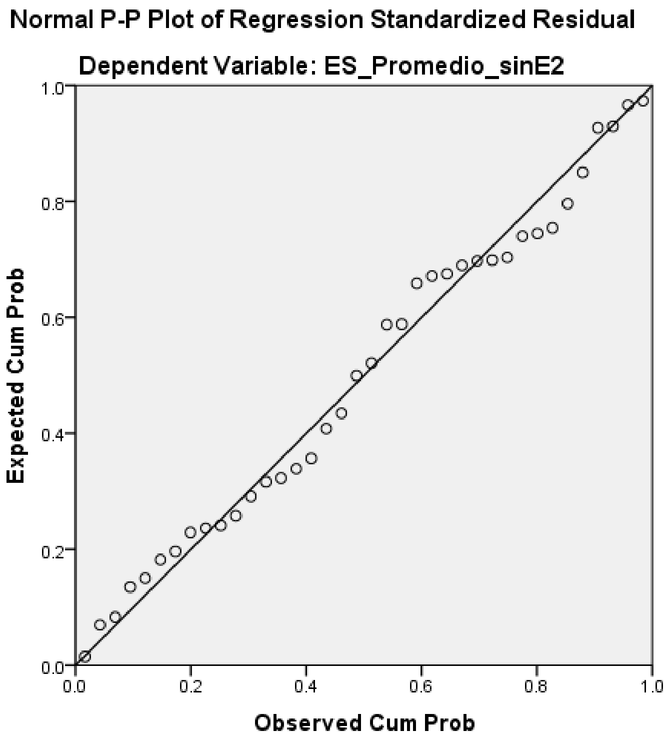
a. Dependent Variable: ES_Promedio_sinE2

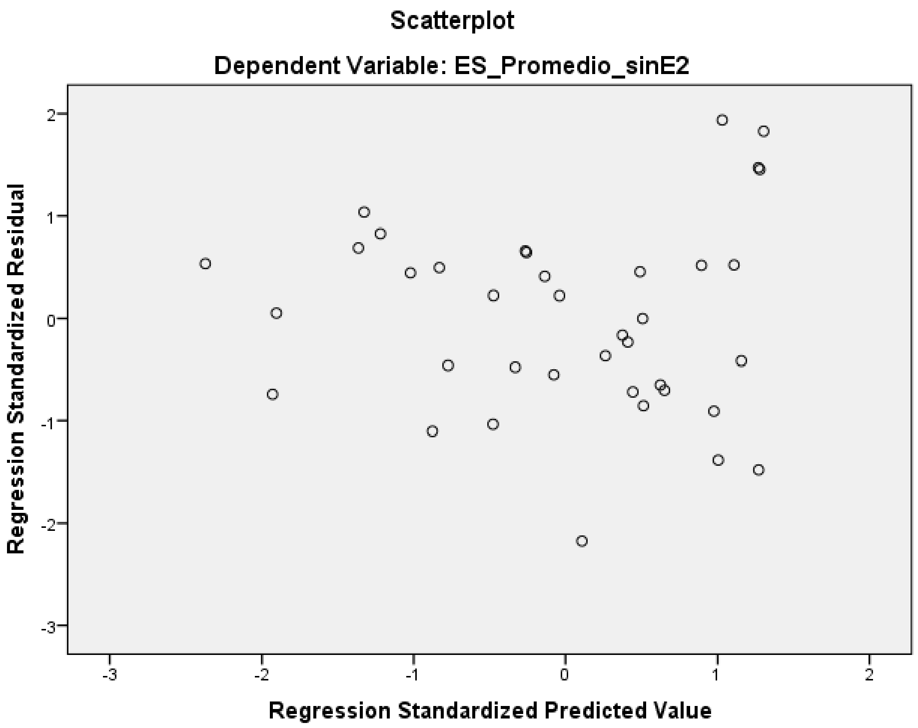
Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.9111	7.5551	5.5526	1.53683	38
Residual	-1.71985	1.53161	.00000	.73534	38
Std. Predicted Value	-2.370	1.303	.000	1.000	38
Std. Residual	-2.175	1.937	.000	.930	38

a. Dependent Variable: ES_Promedio_sinE2




Normal P-P Plot of Regression Standardized Residual
Dependent Variable: ES_Promedio_sinE2
Expected Cum Prob
Observed Cum Prob
0.0
0.2
0.4
0.6
0.8
1.0


Scatterplot
Dependent Variable: ES_Promedio_sinE2
Regression Standardized Residual
Regression Standardized Predicted Value
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2

Asphalt Pavement – Automated Data Collected

Descriptive Statistics

	Mean	Std. Deviation	N
ES_Promedio_sinE2	5.231481	1.8167116	36
Piel de Cocodrilo %	42.549561	46.2097225	36
Trans_Reflexión	15.6402	18.98563	36
Parche Deteriorado %	9.076122	15.4922494	36
Ahuellamiento (mm)	5.547685	7.1551016	36
IRI (m/Km)	8.286111	3.7872080	36

Correlations

		ES_Promedio_sinE2	Piel de Cocodrilo %	Trans_Reflexión	Parche Deteriorado %	Ahuellamiento (mm)	IRI (m/Km)
Pearson Correlation	ES_Promedio_sinE2	1.000	-.795	-.081	-.565	-.285	-.725
	Piel de Cocodrilo %	-.795	1.000	-.324	.456	-.025	.595
	Trans_Reflexión	-.081	-.324	1.000	-.192	-.017	-.029
	Parche Deteriorado %	-.565	.456	-.192	1.000	.107	.356
	Ahuellamiento (mm)	-.285	-.025	-.017	.107	1.000	.039
	IRI (m/Km)	-.725	.595	-.029	.356	.039	1.000
Sig. (1-tailed)	ES_Promedio_sinE2	.	.000	.319	.000	.046	.000
	Piel de Cocodrilo %	.000	.	.027	.003	.443	.000
	Trans_Reflexión	.319	.027	.	.131	.460	.434
	Parche Deteriorado %	.000	.003	.131	.	.267	.017
	Ahuellamiento (mm)	.046	.443	.460	.267	.	.411
	IRI (m/Km)	.000	.000	.434	.017	.411	.
N	ES_Promedio_sinE2	36	36	36	36	36	36
	Piel de Cocodrilo %	36	36	36	36	36	36
	Trans_Reflexión	36	36	36	36	36	36
	Parche Deteriorado %	36	36	36	36	36	36
	Ahuellamiento (mm)	36	36	36	36	36	36
	IRI (m/Km)	36	36	36	36	36	36

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	IRI (m/Km), Trans_Reflexión, Ahuellamiento (mm), Parche Deteriorado %, Piel de Cocodrilo %[b]	.	Enter

a. Dependent Variable: ES_Promedio_sinE2

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.970[a]	.940	.930	.4793677

a. Predictors: (Constant), IRI (m/Km), Trans_Reflexión, Ahuellamiento (mm), Parche Deteriorado %, Piel de Cocodrilo %

b. Dependent Variable: ES_Promedio_sinE2

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	108.622	5	21.724	94.539	.000[b]
	Residual	6.894	30	.230		
	Total	115.515	35			

a. Dependent Variable: ES_Promedio_sinE2

b. Predictors: (Constant), IRI (m/Km), Trans_Reflexión, Ahuellamiento (mm), Parche Deteriorado %, Piel de Cocodrilo %

Coefficients[a]

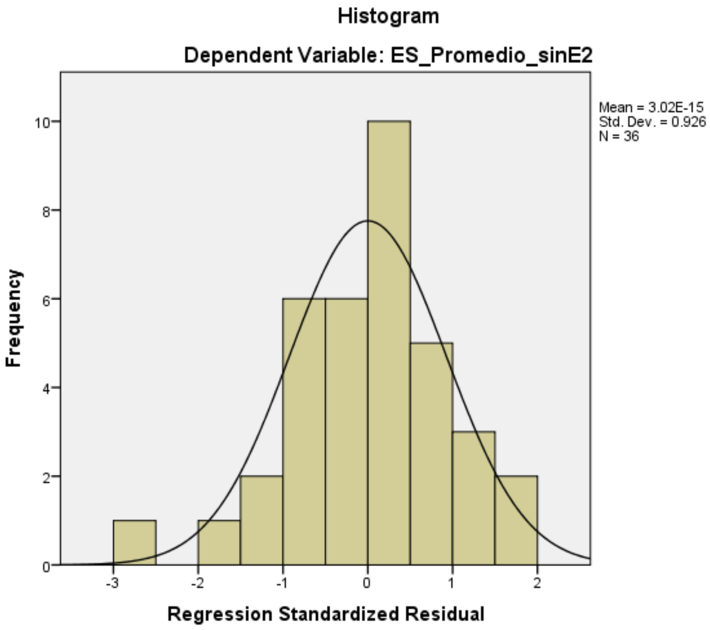
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	8.487	.215		39.423	.000
	Piel de Cocodrilo %	-.026	.002	-.672	-10.696	.000
	Trans_Reflexión	-.034	.005	-.350	-7.227	.000
	Parche Deteriorado %	-.024	.006	-.207	-4.060	.000
	Ahuellamiento (mm)	-.070	.011	-.275	-6.104	.000
	IRI (m/Km)	-.121	.028	-.252	-4.381	.000

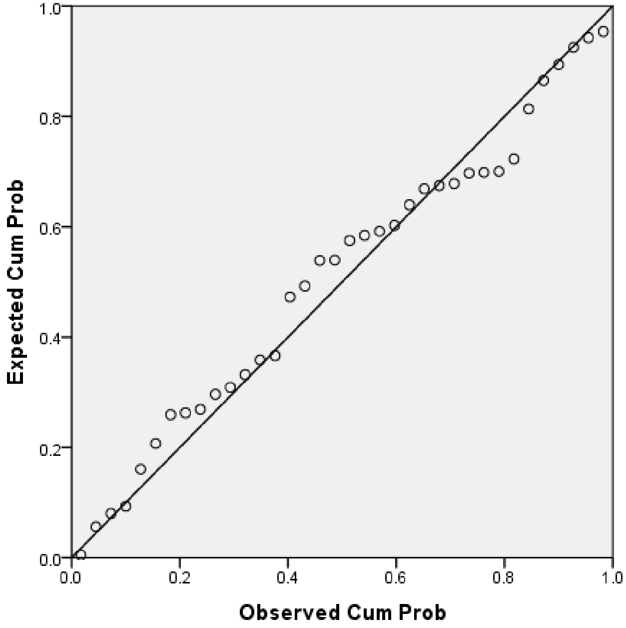
a. Dependent Variable: ES_Promedio_sinE2

Residuals Statistics[a]

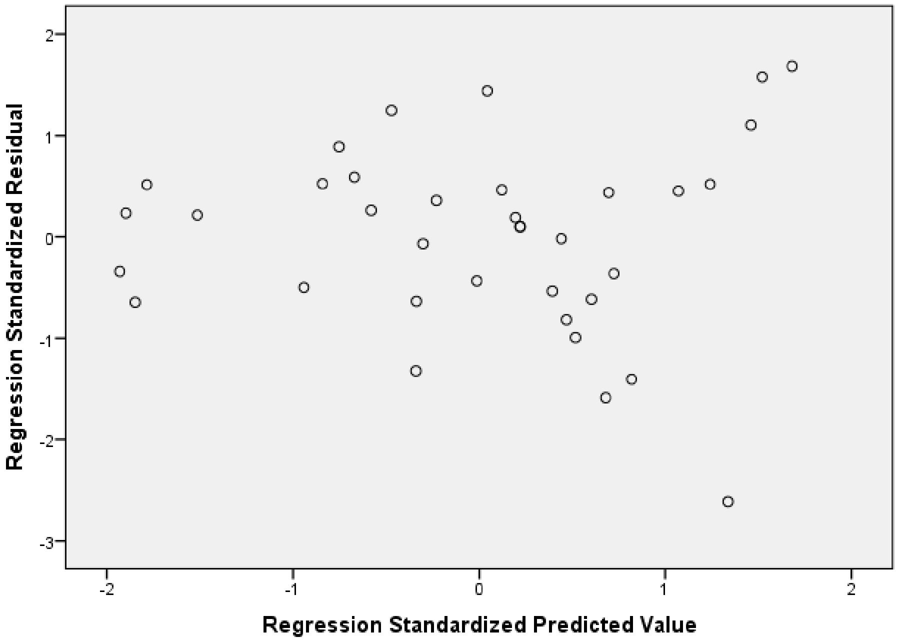
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.830413	8.192987	5.231481	1.7616683	36
Residual	-1.2524375	.8070130	0E-7	.4438083	36
Std. Predicted Value	-1.931	1.681	.000	1.000	36
Std. Residual	-2.613	1.683	.000	.926	36

a. Dependent Variable: ES_Promedio_sinE2




Normal P-P Plot of Regression Standardized Residual

Dependent Variable: ES_Promedio_sinE2


Scatterplot

Dependent Variable: ES_Promedio_sinE2

Asphalt Pavement – Manual Data Collected + IRI

Descriptive Statistics

	Mean	Std. Deviation	N
ES_Promedio_sinE2	5.5526	1.70369	38
PieldeCocodrilo	34.008240	42.2251679	38
Trans_Reflexión	16.6543	19.70511	38
ParcheDeteriorado	6.749204	12.5298272	38
Ahuellamientomm	4.464254	6.5247050	38
IRI	7.8842	3.80686	38

Correlations

		ES_Promedio_sinE2	PieldeCocodrilo	Trans_Reflexión	ParcheDeteriorado	Ahuellamientomm	IRI
Pearson Correlation	ES_Promedio_sinE2	1.000	-.723	-.243	-.466	-.334	-.660
	PieldeCocodrilo	-.723	1.000	-.249	.336	.066	.575
	Trans_Reflexión	-.243	-.249	1.000	-.148	.176	-.038
	ParcheDeteriorado	-.466	.336	-.148	1.000	.156	.292
	Ahuellamientomm	-.334	.066	.176	.156	1.000	.099
	IRI	-.660	.575	-.038	.292	.099	1.000
Sig. (1-tailed)	ES_Promedio_sinE2	.	.000	.071	.002	.020	.000
	PieldeCocodrilo	.000	.	.066	.020	.347	.000
	Trans_Reflexión	.071	.066	.	.187	.145	.411
	ParcheDeteriorado	.002	.020	.187	.	.175	.038
	Ahuellamientomm	.020	.347	.145	.175	.	.276
	IRI	.000	.000	.411	.038	.276	.
N	ES_Promedio_sinE2	38	38	38	38	38	38
	PieldeCocodrilo	38	38	38	38	38	38
	Trans_Reflexión	38	38	38	38	38	38
	ParcheDeteriorado	38	38	38	38	38	38
	Ahuellamientomm	38	38	38	38	38	38
	IRI	38	38	38	38	38	38

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	IRI, Trans_Reflexión, Ahuellamientomm, ParcheDeteriorado, PieldeCocodrilo[b]	.	Enter

a. Dependent Variable: ES_Promedio_sinE2

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.924[a]	.853	.830	.70236

a. Predictors: (Constant), IRI, Trans_Reflexión, Ahuellamientomm, ParcheDeteriorado, PieldeCocodrilo

b. Dependent Variable: ES_Promedio_sinE2

ANOVA[a]

Model		Sum of Squares	Df	Mean Square	F	Sig.
1	Regression	91.609	5	18.322	37.141	.000[b]
	Residual	15.786	32	.493		
	Total	107.395	37			

a. Dependent Variable: ES_Promedio_sinE2

b. Predictors: (Constant), IRI, Trans_Reflexión, Ahuellamientomm, ParcheDeteriorado, PieldeCocodrilo

Coefficients[a]

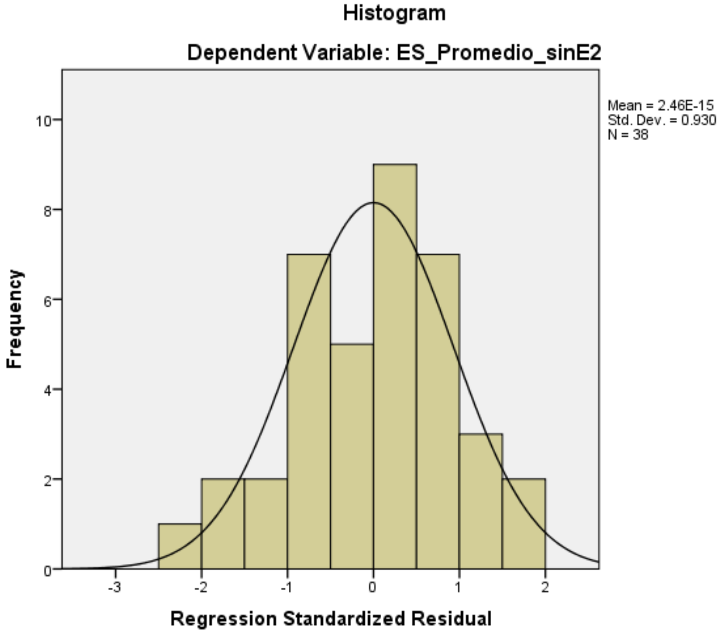
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	8.235	.289		28.453	.000
	PieldeCocodrilo	-.024	.004	-.592	-6.740	.000
	Trans_Reflexión	-.035	.006	-.405	-5.588	.000
	ParcheDeteriorado	-.031	.010	-.228	-3.095	.004
	Ahuellamientomm	-.043	.018	-.163	-2.319	.027
	IRI	-.113	.038	-.252	-2.979	.005

a. Dependent Variable: ES_Promedio_sinE2

Residuals Statistics[a]

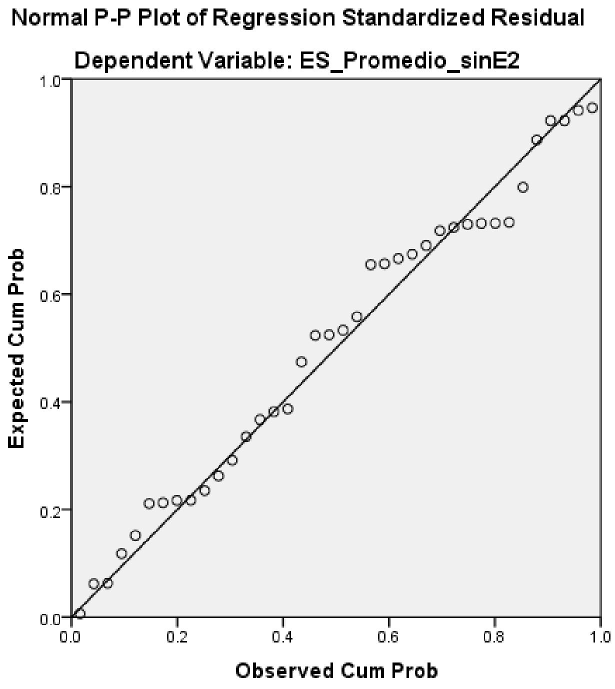
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.2010	8.0007	5.5526	1.57351	38
Residual	-1.74546	1.13233	.00000	.65318	38
Std. Predicted Value	-2.766	1.556	.000	1.000	38
Std. Residual	-2.485	1.612	.000	.930	38

a. Dependent Variable: ES_Promedio_sinE2

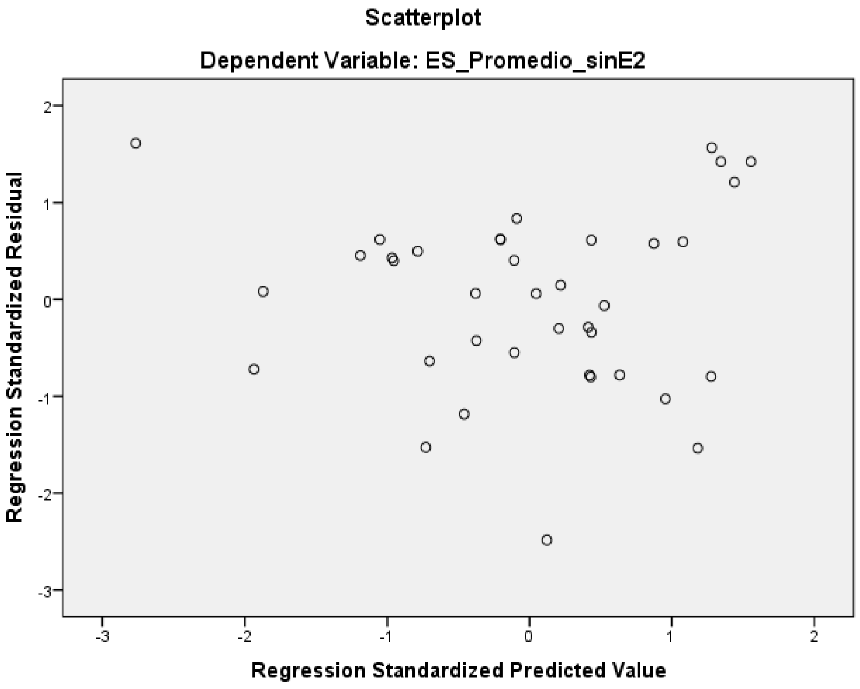


Histogram

Dependent Variable: ES_Promedio_sinE2


Normal P-P Plot of Regression Standardized Residual

Dependent Variable: ES_Promedio_sinE2


Scatterplot

Dependent Variable: ES_Promedio_sinE2

Concrete Pavement – Manual Data Collected

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Sellos, Esc., PD, EsqOblic, Long, Trans[b]	.	Enter

a. Dependent Variable: ICPU OBS

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.902[a]	.814	.794	1.096

a. Predictors: (Constant), Sellos, Esc., PD, EsqOblic, Long, Trans

b. Dependent Variable: ICPU OBS

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	284.761	6	47.460	39.483	.000[b]
	Residual	64.911	54	1.202		
	Total	349.672	60			

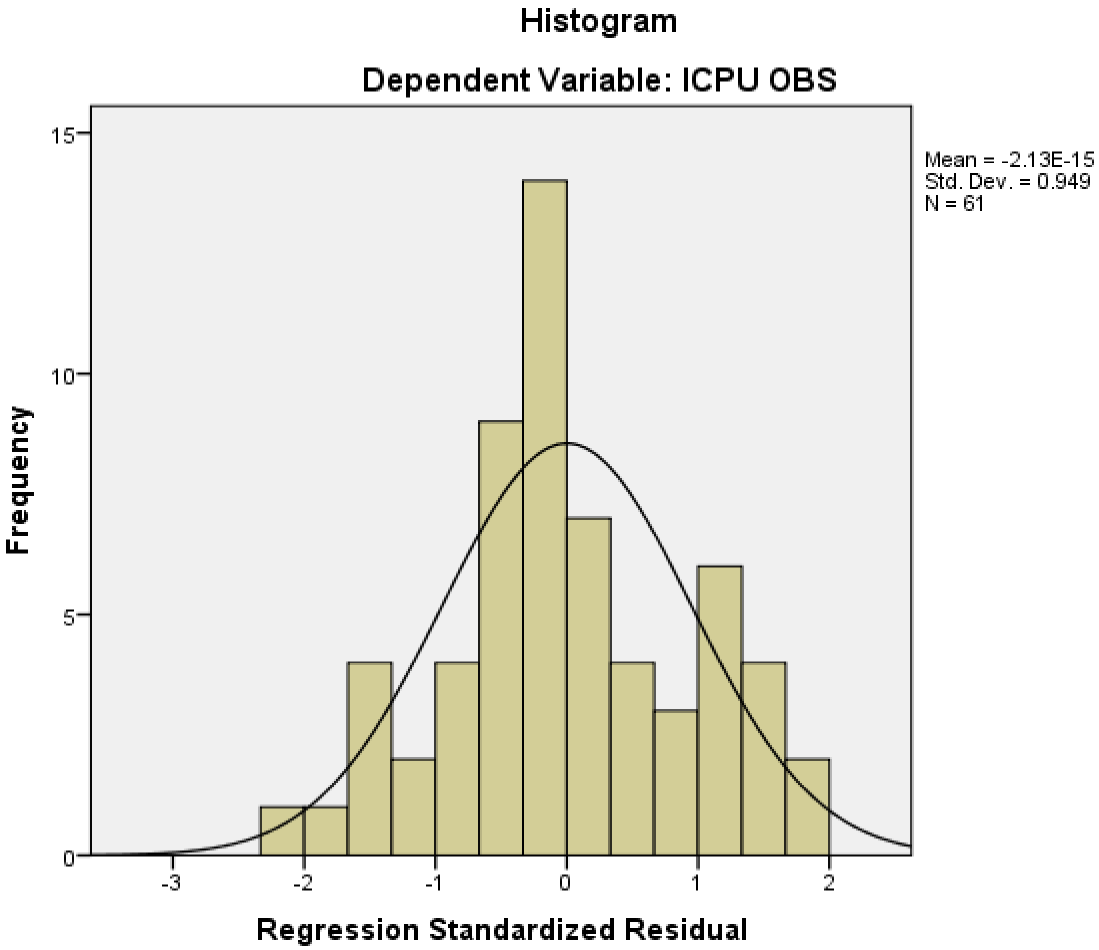
a. Dependent Variable: ICPU OBS

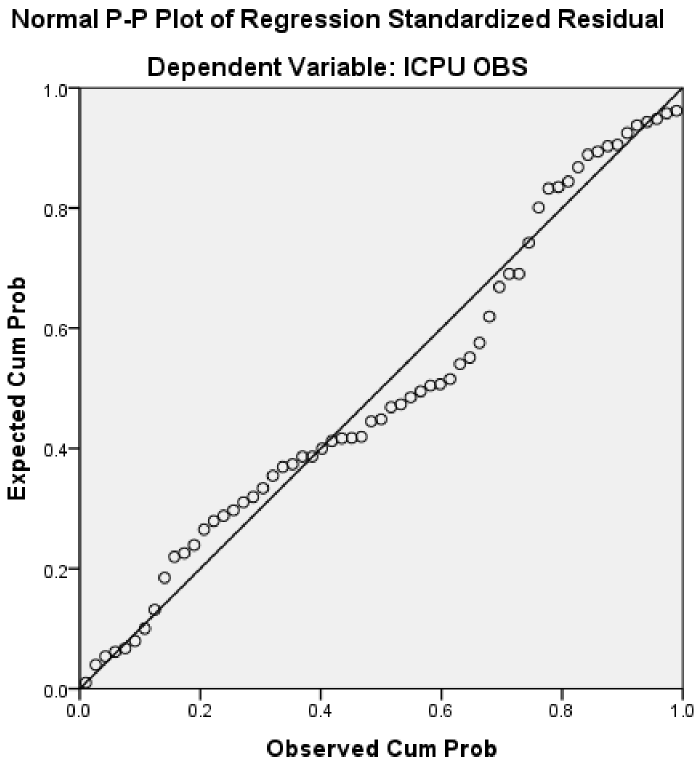
b. Predictors: (Constant), Sellos, Esc., PD, EsqOblic, Long, Trans

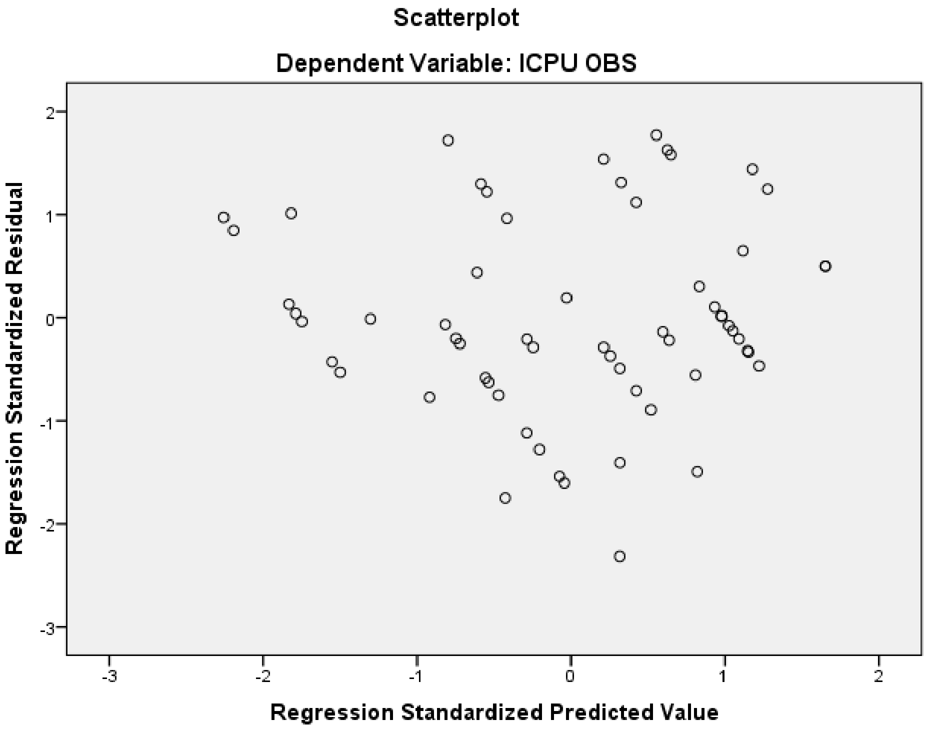
Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	9.455	.412		22.935	.000
	Long	-.040	.007	-.374	-5.857	.000
	Trans	-.024	.006	-.389	-4.080	.000
	PD	-.060	.019	-.274	-3.220	.002
	Esc.	-.249	.069	-.247	-3.616	.001
	EsqOblic	-.036	.016	-.144	-2.209	.031
	Sellos	-.017	.007	-.168	-2.685	.010

a. Dependent Variable: ICPU OBS




Normal P-P Plot of Regression Standardized Residual
Dependent Variable: ICPU OBS
Expected Cum Prob
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Observed Cum Prob


Scatterplot
Dependent Variable: ICPU OBS
Regression Standardized Residual
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
Regression Standardized Predicted Value

Appendix G

Transition Probability Matrices

TPM and CTM for Asphalt Pavement-Mediterranean Climate-Secondary Network

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	46	24	21	9	0	0	0	0	0	100
8.99 - 8.00	0	50	39	2	9	0	0	0	0	100
7.99 - 7.00	0	0	44	46	10	0	0	0	0	100
6.99 - 6.00	0	0	0	52	48	0	0	0	0	100
5.99 - 5.00	0	0	0	0	52	28	20	0	0	100
4.99 - 4.00	0	0	0	0	0	50	0	50	0	100
3.99 - 3.00	0	0	0	0	0	0	78	22	0	100
2.99 - 2.00	0	0	0	0	0	0	0	0	0	0
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	46	70	91	100	100	100	100	100	100
8.99 - 8.00	0	50	89	91	100	100	100	100	100
7.99 - 7.00	0	0	44	90	100	100	100	100	100
6.99 - 6.00	0	0	0	52	100	100	100	100	100
5.99 - 5.00	0	0	0	0	52	80	100	100	100
4.99 - 4.00	0	0	0	0	0	50	50	100	100
3.99 - 3.00	0	0	0	0	0	0	78	100	100
2.99 - 2.00	0	0	0	0	0	0	0	0	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Asphalt Pavement-Mediterranean Climate-Local Network

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	36	41	23	0	0	0	0	0	0	100
8.99 - 8.00	0	100	0	0	0	0	0	0	0	100
7.99 - 7.00	0	0	100	0	0	0	0	0	0	100
6.99 - 6.00	0	0	0	61	6	33	0	0	0	100
5.99 - 5.00	0	0	0	0	100	0	0	0	0	100
4.99 - 4.00	0	0	0	0	0	89	11	0	0	100
3.99 - 3.00	0	0	0	0	0	0	0	100	0	100
2.99 - 2.00	0	0	0	0	0	0	0	40	60	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	36	77	100	100	100	100	100	100	100
8.99 - 8.00	0	90	100	100	100	100	100	100	100
7.99 - 7.00	0	0	90	100	100	100	100	100	100
6.99 - 6.00	0	0	0	61	67	100	100	100	100
5.99 - 5.00	0	0	0	0	90	100	100	100	100
4.99 - 4.00	0	0	0	0	0	89	100	100	100
3.99 - 3.00	0	0	0	0	0	0	0	100	100
2.99 - 2.00	0	0	0	0	0	0	0	40	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Asphalt Pavement-Mediterranean Climate-TD ≤ SC

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	86	9	5	0	0	0	0	0	0	100
8.99 - 8.00	0	81	19	0	0	0	0	0	0	100
7.99 - 7.00	0	0	54	31	15	0	0	0	0	100
6.99 - 6.00	0	0	0	57	43	0	0	0	0	100
5.99 - 5.00	0	0	0	0	59	41	0	0	0	100
4.99 - 4.00	0	0	0	0	0	85	15	0	0	100
3.99 - 3.00	0	0	0	0	0	0	27	73	0	100
2.99 - 2.00	0	0	0	0	0	0	0	40	60	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	86	95	100	100	100	100	100	100	100
8.99 - 8.00	0	81	100	100	100	100	100	100	100
7.99 - 7.00	0	0	54	85	100	100	100	100	100
6.99 - 6.00	0	0	0	57	100	100	100	100	100
5.99 - 5.00	0	0	0	0	59	100	100	100	100
4.99 - 4.00	0	0	0	0	0	85	100	100	100
3.99 - 3.00	0	0	0	0	0	0	27	100	100
2.99 - 2.00	0	0	0	0	0	0	0	40	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Asphalt Pavement-Mediterranean Climate-TD > SC

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	54	25	8	12	0	0	0	0	0	100
8.99 - 8.00	0	36	53	11	0	0	0	0	0	100
7.99 - 7.00	0	0	57	26	16	0	0	0	0	100
6.99 - 6.00	0	0	0	62	31	0	8	0	0	100
5.99 - 5.00	0	0	0	0	89	11	0	0	0	100
4.99 - 4.00	0	0	0	0	0	66	34	0	0	100
3.99 - 3.00	0	0	0	0	0	0	53	0	47	100
2.99 - 2.00	0	0	0	0	0	0	0	50	50	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	54	79	88	100	100	100	100	100	100
8.99 - 8.00	0	36	89	100	100	100	100	100	100
7.99 - 7.00	0	0	57	84	100	100	100	100	100
6.99 - 6.00	0	0	0	62	92	92	100	100	100
5.99 - 5.00	0	0	0	0	89	100	100	100	100
4.99 - 4.00	0	0	0	0	0	66	100	100	100
3.99 - 3.00	0	0	0	0	0	0	53	53	100
2.99 - 2.00	0	0	0	0	0	0	0	50	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Mediterranean Climate-Primary Network

Current Condition *i*	Future Condition *j*									Sum
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	77	12	12	0	0	0	0	0	0	100
8.99 - 8.00	0	57	43	0	0	0	0	0	0	100
7.99 - 7.00	0	0	60	34	0	6	0	0	0	100
6.99 - 6.00	0	0	0	58	34	8	0	0	0	100
5.99 - 5.00	0	0	0	0	76	24	0	0	0	100
4.99 - 4.00	0	0	0	0	0	56	44	0	0	100
3.99 - 3.00	0	0	0	0	0	0	100	0	0	100
2.99 - 2.00	0	0	0	0	0	0	0	0	0	0
1.99 - 1.00	0	0	0	0	0	0	0	0	0	0

Current Condition *i*	Future Condition *j*								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	77	88	100	100	100	100	100	100	100
8.99 - 8.00	0	57	100	100	100	100	100	100	100
7.99 - 7.00	0	0	60	94	94	100	100	100	100
6.99 - 6.00	0	0	0	58	92	100	100	100	100
5.99 - 5.00	0	0	0	0	76	100	100	100	100
4.99 - 4.00	0	0	0	0	0	56	100	100	100
3.99 - 3.00	0	0	0	0	0	0	90	100	100
2.99 - 2.00	0	0	0	0	0	0	0	0	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Mediterranean Climate-Secondary Network

Current Condition *i*	Future Condition *j*									Sum
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	14	71	15	0	0	0	0	0	0	100
8.99 - 8.00	0	67	33	0	0	0	0	0	0	100
7.99 - 7.00	0	0	28	57	8	7	0	0	0	100
6.99 - 6.00	0	0	0	83	8	8	0	0	0	100
5.99 - 5.00	0	0	0	0	38	55	6	0	0	100
4.99 - 4.00	0	0	0	0	0	88	12	0	0	100
3.99 - 3.00	0	0	0	0	0	0	36	64	0	100
2.99 - 2.00	0	0	0	0	0	0	0	0	0	0
1.99 - 1.00	0	0	0	0	0	0	0	0	0	0

Current Condition *i*	Future Condition *j*								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	14	85	100	100	100	100	100	100	100
8.99 - 8.00	0	67	100	100	100	100	100	100	100
7.99 - 7.00	0	0	28	85	93	100	100	100	100
6.99 - 6.00	0	0	0	83	92	100	100	100	100
5.99 - 5.00	0	0	0	0	38	94	100	100	100
4.99 - 4.00	0	0	0	0	0	88	100	100	100
3.99 - 3.00	0	0	0	0	0	0	36	100	100
2.99 - 2.00	0	0	0	0	0	0	0	0	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Mediterranean Climate-Local Network

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	100	0	0	0	0	0	0	0	0	100
8.99 - 8.00	0	74	18	8	0	0	0	0	0	100
7.99 - 7.00	0	0	66	13	21	0	0	0	0	100
6.99 - 6.00	0	0	0	49	45	5	0	0	0	100
5.99 - 5.00	0	0	0	0	100	0	0	0	0	100
4.99 - 4.00	0	0	0	0	0	60	40	0	0	100
3.99 - 3.00	0	0	0	0	0	0	52	48	0	100
2.99 - 2.00	0	0	0	0	0	0	0	82	18	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	90	100	100	100	100	100	100	100	100
8.99 - 8.00	0	74	92	100	100	100	100	100	100
7.99 - 7.00	0	0	66	79	100	100	100	100	100
6.99 - 6.00	0	0	0	49	95	100	100	100	100
5.99 - 5.00	0	0	0	0	90	100	100	100	100
4.99 - 4.00	0	0	0	0	0	60	100	100	100
3.99 - 3.00	0	0	0	0	0	0	52	100	100
2.99 - 2.00	0	0	0	0	0	0	0	82	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Mediterranean Climate-TD ≤ SC

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	57	29	13	0	0	0	0	0	0	100
8.99 - 8.00	0	68	29	3	0	0	0	0	0	100
7.99 - 7.00	0	0	48	44	5	4	0	0	0	100
6.99 - 6.00	0	0	0	64	26	10	0	0	0	100
5.99 - 5.00	0	0	0	0	62	34	4	0	0	100
4.99 - 4.00	0	0	0	0	0	83	17	0	0	100
3.99 - 3.00	0	0	0	0	0	0	43	57	0	100
2.99 - 2.00	0	0	0	0	0	0	0	82	18	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	57	87	100	100	100	100	100	100	100
8.99 - 8.00	0	68	97	100	100	100	100	100	100
7.99 - 7.00	0	0	48	91	96	100	100	100	100
6.99 - 6.00	0	0	0	64	90	100	100	100	100
5.99 - 5.00	0	0	0	0	62	96	100	100	100
4.99 - 4.00	0	0	0	0	0	83	100	100	100
3.99 - 3.00	0	0	0	0	0	0	43	100	100
2.99 - 2.00	0	0	0	0	0	0	0	82	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Mediterranean Climate-TD > SC

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	0	100	0	0	0	0	0	0	0	100
8.99 - 8.00	0	46	54	0	0	0	0	0	0	100
7.99 - 7.00	0	0	44	25	20	11	0	0	0	100
6.99 - 6.00	0	0	0	57	43	0	0	0	0	100
5.99 - 5.00	0	0	0	0	70	30	0	0	0	100
4.99 - 4.00	0	0	0	0	0	83	17	0	0	100
3.99 - 3.00	0	0	0	0	0	0	89	11	0	100
2.99 - 2.00	0	0	0	0	0	0	0	94	6	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	0	100	100	100	100	100	100	100	100
8.99 - 8.00	0	46	100	100	100	100	100	100	100
7.99 - 7.00	0	0	44	69	89	100	100	100	100
6.99 - 6.00	0	0	0	57	100	100	100	100	100
5.99 - 5.00	0	0	0	0	70	100	100	100	100
4.99 - 4.00	0	0	0	0	0	83	100	100	100
3.99 - 3.00	0	0	0	0	0	0	89	100	100
2.99 - 2.00	0	0	0	0	0	0	0	94	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Asphalt Pavement-Dry Climate-Global

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	89	9	0	2	0	0	0	0	0	100
8.99 - 8.00	0	32	56	13	0	0	0	0	0	100
7.99 - 7.00	0	0	50	46	3	0	0	0	0	100
6.99 - 6.00	0	0	0	24	50	11	15	0	0	100
5.99 - 5.00	0	0	0	0	30	49	0	21	0	100
4.99 - 4.00	0	0	0	0	0	50	50	0	0	100
3.99 - 3.00	0	0	0	0	0	0	26	74	0	100
2.99 - 2.00	0	0	0	0	0	0	0	76	24	100
1.99 - 1.00	0	0	0	0	0	0	0	5	95	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	83	96	97	100	100	100	100	100	100
8.99 - 8.00	0	42	87	100	100	100	100	100	100
7.99 - 7.00	0	0	50	93	100	100	100	100	100
6.99 - 6.00	0	0	0	15	46	69	100	100	100
5.99 - 5.00	0	0	0	0	30	79	79	100	100
4.99 - 4.00	0	0	0	0	0	50	100	100	100
3.99 - 3.00	0	0	0	0	0	0	26	100	100
2.99 - 2.00	0	0	0	0	0	0	0	70	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

TPM and CTM for Concrete Pavement-Humid Climate-Global

Current Condition *i*	**Future Condition *j***									**Sum**
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00	
10.00 - 9.00	85	15	0	0	0	0	0	0	0	100
8.99 - 8.00	0	95	5	0	0	0	0	0	0	100
7.99 - 7.00	0	0	62	33	5	0	0	0	0	100
6.99 - 6.00	0	0	0	85	15	0	0	0	0	100
5.99 - 5.00	0	0	0	0	51	35	13	0	0	100
4.99 - 4.00	0	0	0	0	0	50	50	0	0	100
3.99 - 3.00	0	0	0	0	0	0	66	34	0	100
2.99 - 2.00	0	0	0	0	0	0	0	63	37	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100	100

Current Condition *i*	**Future Condition *j***								
	10.00 - 9.00	8.99 - 8.00	7.99 - 7.00	6.99 - 6.00	5.99 - 5.00	4.99 - 4.00	3.99 - 3.00	2.99 - 2.00	1.99 - 1.00
10.00 - 9.00	76	100	100	100	100	100	100	100	100
8.99 - 8.00	0	88	100	100	100	100	100	100	100
7.99 - 7.00	0	0	73	89	100	100	100	100	100
6.99 - 6.00	0	0	0	65	100	100	100	100	100
5.99 - 5.00	0	0	0	0	43	84	100	100	100
4.99 - 4.00	0	0	0	0	0	46	100	100	100
3.99 - 3.00	0	0	0	0	0	0	58	100	100
2.99 - 2.00	0	0	0	0	0	0	0	63	100
1.99 - 1.00	0	0	0	0	0	0	0	0	100

Appendix H

Validation Tests for Performance Models

Asphalt Pavements – Mediterranean Climate – Primary Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.947889347	6.689761882
Varianza	9.140325491	10.36811372
Observaciones	11	11
Diferencia hipotética de las medias	0	
Grados de libertad	20	
Estadístico t	0.193829241	
P(T<=t) una cola	0.424132343	
Valor crítico de t (una cola)	1.724718243	
P(T<=t) dos colas	0.848264687	
Valor crítico de t (dos colas)	2.085963447	

Asphalt Pavements – Mediterranean Climate – Secondary Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	5.532329755	5.2162418
Varianza	6.012791089	5.803021665
Observaciones	10	10
Diferencia hipotética de las medias	0	
Grados de libertad	18	
Estadístico t	0.290787777	
P(T<=t) una cola	0.387268783	
Valor crítico de t (una cola)	1.734063607	
P(T<=t) dos colas	0.774537566	
Valor crítico de t (dos colas)	2.10092204	

Asphalt Pavements – Mediterranean Climate – Local Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.996853454	7.108729642
Varianza	1.961927552	1.999107737
Observaciones	14	14
Diferencia hipotética de las medias	0	
Grados de libertad	26	
Estadístico t	-0.210328112	
P(T<=t) una cola	0.417525602	
Valor crítico de t (una cola)	1.70561792	
P(T<=t) dos colas	0.835051204	
Valor crítico de t (dos colas)	2.055529439	

Asphalt Pavements – Mediterranean Climate – Traffic Demand ≤ Structural Capacity

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.629881694	6.718710301
Varianza	5.096845563	5.508102444
Observaciones	25	25
Diferencia hipotética de las medias	0	
Grados de libertad	48	
Estadístico t	-0.13638562	
P(T<=t) una cola	0.446043431	
Valor crítico de t (una cola)	2.010634758	
P(T<=t) dos colas	0.892086863	
Valor crítico de t (dos colas)	2.313899132	

Asphalt Pavements – Mediterranean Climate – Traffic Demand >Structural Capacity

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.480072177	6.130116423
Varianza	8.916558529	7.695027361
Observaciones	6	6
Diferencia hipotética de las medias	0	
Grados de libertad	10	
Estadístico t	0.21032128	
P(T<=t) una cola	0.418820231	
Valor crítico de t (una cola)	2.228138852	
P(T<=t) dos colas	0.837640463	
Valor crítico de t (dos colas)	2.633766916	

Concrete Pavements – Mediterranean Climate – Primary Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.556756692	6.581566977
Varianza	1.966874713	2.332270947
Observaciones	22	22
Diferencia hipotética de las medias	0	
Grados de libertad	42	
Estadístico t	-0.056124439	
P(T<=t) una cola	0.477754413	
Valor crítico de t (una cola)	1.681952357	
P(T<=t) dos colas	0.955508827	
Valor crítico de t (dos colas)	2.018081703	

Concrete Pavements – Mediterranean Climate – Secondary Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.505092068	6.419231729
Varianza	2.928865943	2.308749098
Observaciones	22	22
Diferencia hipotética de las medias	0	
Grados de libertad	41	
Estadístico t	0.1759694	
P(T<=t) una cola	0.430592132	
Valor crítico de t (una cola)	1.682878002	
P(T<=t) dos colas	0.861184263	
Valor crítico de t (dos colas)	2.01954097	

Concrete Pavements – Mediterranean Climate – Local Network

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.425117109	6.517439073
Varianza	3.418206177	3.111736409
Observaciones	10	10
Diferencia hipotética de las medias	0	
Grados de libertad	18	
Estadístico t	-0.11424846	
P(T<=t) una cola	0.455152783	
Valor crítico de t (una cola)	1.734063607	
P(T<=t) dos colas	0.910305565	
Valor crítico de t (dos colas)	2.10092204	

Concrete Pavements – Mediterranean Climate – Traffic Demand ≤ Structural Capacity

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.308938159	6.354103184
Varianza	3.502854875	2.927049339
Observaciones	49	49
Diferencia hipotética de las medias	0	
Grados de libertad	95	
Estadístico t	-0.124680359	
P(T<=t) una cola	0.450520027	
Valor crítico de t (una cola)	1.985251004	
P(T<=t) dos colas	0.901040054	
Valor crítico de t (dos colas)	2.277482763	

Concrete Pavements – Mediterranean Climate – Traffic Demand >Structural Capacity

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	5.73463843	5.747789897
Varianza	1.932928408	1.213306396
Observaciones	8	8
Diferencia hipotética de las medias	0	
Grados de libertad	13	
Estadístico t	-0.020971217	
P(T<=t) una cola	0.491793541	
Valor crítico de t (una cola)	2.160368656	
P(T<=t) dos colas	0.983587083	
Valor crítico de t (dos colas)	2.532637815	

Asphalt Pavement – Dry Climate – Global

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	7.276644881	7.219599363
Varianza	7.532730866	7.249751122
Observaciones	32	32
Diferencia hipotética de las medias	0	
Grados de libertad	62	
Estadístico t	0.083931086	
P(T<=t) una cola	0.46669082	
Valor crítico de t (una cola)	1.669804163	
P(T<=t) dos colas	0.93338164	
Valor crítico de t (dos colas)	1.998971517	

Concrete Pavement – Humid Climate – Global

Prueba t para dos muestras suponiendo varianzas desiguales		
	UPCI 2	*UPCICALC*
Media	6.737876227	6.493700321
Varianza	3.312091008	4.141108608
Observaciones	17	17
Diferencia hipotética de las medias	0	
Grados de libertad	32	
Estadístico t	0.368770262	
P(T<=t) una cola	0.35736384	
Valor crítico de t (una cola)	2.036933343	
P(T<=t) dos colas	0.71472768	
Valor crítico de t (dos colas)	2.35183518	

Appendix I

Summary of P&M&R Treatments

Asphalt Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
Pothole Repair	Rutine Maintenance	Anual Low or moderate Cracking and young pavement Moderate or high fatigue cracking and raveling Moderate fatigue cracking; moderate deteriorated patches; moderate and high rutting	Up to 80 m2/Km/year		3 to 5	Manvu; MOP, 2003; MOP, 2012; Hicks
Deep Patches	Rehabilitation	Moderate or high fatigue cracking; moderate deteriorated patches; Moderate raveling; high, moderate or low rutting				(Hicks et al. 2000)
Seals	Preservation	Cracking Area>15% Cracking Area >20% Cracking Area >25%				MOP, 2003; Manvu
Seal coat	Preservation	Young pavement, Moderate raveling			3 to 6	(Hicks et al. 2000)
Sand seal	Preservation	Low cracking, aging	Low traffic		2 to 5	(Hicks et al. 2000)

Asphalt Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
Slurry Seal	Preservation	Cracking Area >10% Cracking Area >15% Cracking Area >20% Cracking Area >25% Aging, raveling or Fatigue cracking ≤ 10%. Rutting < 0.5" Fatigue, block, longitudinal, transversal and reflection cracking of low severity and raveling Low cracking, raveling, aging	All type of climate and traffic Improve: friction, roughness, service life Not Recommended for high roughness, high cracking, fatigue cracking, high rutting or high bleeding	Best condition	3 to 4 2 to 5	MOP, 2003; MOP, 2006; MOP, 2012; Caltrans, Hicks; NCHRP Peshkin; Ontario; 22 Hicks; Hicks (Ohio DOT) Table B.2
Fog Seal	Preservation	Raveling, shrinkage, aging, fatigue cracking ≤ 10%.	No structural deterioration		1 1 to 2 Not much effect in service life	(Hicks et al. 2000)
Fog Seal	Preservation	Raveling, shrinkage, aging, fatigue cracking ≤ 10%	No structural deterioration Low traffic		1 1 to 2 Not much effect in service life	(Hicks et al. 2000)
Fog Seal	Preservation	Raveling, shrinkage, aging, fatigue cracking ≤ 10%.	No structural deterioration Low Traffic		1 1 to 2 Not much effect in service life	11 Hicks; 1 Hicks; Caltrans, Hicks; Hicks (Ohio DOT) Table B.2; NCHRP Peshkin
Chip seal	Preservation	Raveling, aging, fatigue cracking ≤ 20%. Or rutting. < 0.5" Moderate/low Block cracking	Low IRI, Low Rutting for AADT<1000 Raveling, weathering, longitudinal and transversal		3 to 6 4 to 8	11 Hicks, 1 Hicks, (Caltrans, Hicks) NCHRP Peshkin, Ontario

Asphalt Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
		and/or bleeding Friction, raveling, low cracking, aging	cracking for AADT≤5000 Block Cracking Any Climate type, AADT<30000 Improve: Friction, roughness and service life Not Recommended for high roughness, high fatigue cracking, high rutting or high bleeding Not recommended for urban pavements			(Hicks et al. 2000)
Microsurfacing	Preservation	Low IRI, Low Rutting, raveling, weathering, bleeding Aging, raveling or fatigue cracking ≤ 10% o rutting < 0.5"	AADT ≥ 1000 All climate types, AADT < 5000 Not recommended for high roughness, high fatigue cracking or high rutting.		3 to 4 2 to 6 3 to 8	(Hicks et al. 2000)
Crack sealing	Rutine Maintenance	Fatigue Cracking ≤ 10% or longitudinal of tranversal cracking Low or moderate cracking Low fatigue cracking, block cracking, low or moderate reflection, long and trans cracking; low ofr moderate deteriorated patch	Not recommended for high roughness, high fatigue cracking, raveling or high rutting. Poor effectivity for high long or trans cracking for AADT > 5000		1 to 2 1 to 4 3 to 5 Not effective for improving service life	(Hicks et al. 2000)
Crack sealing with modified asphalt	Rutine Maintenance	Grietas fatiga o grietas long o trans	All types of climate and traffic		2 to 3	(Hicks et al. 2000)
Thin Overlay	Preservation	Low Cracking > 40% IRI ≥ 3,5 m/Km	Low IRI, low rutting, long or trans cracking, shrinkage		3 to 6 Increase	Manvu 11 Hicks; 1 Hicks; 16

Asphalt Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
		Friction, raveling	for AADT > 5000		Service Life	(Hicks et al. 2000)
Thin Overlay	Preservation	Rutting, low cracking aging. All types of traffic Low or moderate structural deterioration Moderate age and cracking Moderate and high serviceability and moderate or high raveling	Low/Moderate block cracking, raveling, polished aggregate All types of climate and traffic AADT<300 p/ 50mm, 300<AADT<1200 p/ 60mm Improve: friction, roughness, service life Not recommended for high fatigue cracking, high roughness, high rutting		7 to 10 4 to 8 6 to 9 8 to 11	(Hicks et al. 2000)
Overlay with Open Grade AC	Preservation	Aging, raveling or fatigue cracking ≤ 20%	All types of climate and traffic		3 to 5	(Hicks et al. 2000)
Overlay with AR	Preservation	Aging, raveling or fatigue cracking ≤ 30% or rutting. < 0.5"	All types of climate and traffic		4 to 6	(Hicks et al. 2000)
Thin Overlay with PBA	Preservation	Aging, raveling or fatigue cracking ≤ 30% o rutting	All types of climate and traffic		3 to 6	(Hicks et al. 2000)
Thin Overlay R (G Type)	Preservation	Aging, raveling or fatigue cracking ≤ 30% o rutting.	All types of climate and traffic		5 to 8	(Hicks et al. 2000)
Milling and Overlay (different thickness)	Maintenance	Fatigue cracking ≤ 2% y Rutting. ≤ 15				(Hicks et al. 2000)

Asphalt Pavements

Maintenance Activities	Maintenance Type	Application Policy	Recommendations for Application	Effect on ICPU	Service Life	Reference
Structural Overlay	Maintenance	IRI ≥ 4 m/Km IRI ≥ 5 m/Km IRI ≥ 3,5 m/Km 2 < SL ≤ 2.5 and Fatigue cracking ≤ 2% and Rutting. < 5 High cracking, moderate structural deterioration, old pavement, high or moderate rutting and deteriorated patches	All types of climate and traffic Crack seal, pothol repair previous	Condición Nueva IRI=1,5 m/Km	8 a 12	MOP, 2003; MOP, 2006 (Hicks et al. 2000)
Cold Recycling	Rehabilitation	Raveling, rutting, low cracking, aging. Moderate age; Moderate/High block cracking	Low traffic For high traffic requires overlay		5 to 10 5 to 8	(Hicks et al. 2000)
Hot Recycling	Rehabilitation	Rutting, low cracking, aging. Moderate/high block cracking, high long transo or reflection cracking; high deteriorated patch; raveling and high rutting ahuellamiento alto	Alto tránsito		5 to 10	(Hicks et al. 2000)
Reconstruction with Seals	Rehabilitation	IRI ≥ 8 m/Km	300<TMDA<1200			MOP, 2003; MOP, 2012
Reconstruction (different structures)	Rehabilitation	IRI ≥ 6 m/Km 10% < Fatigue Cracking or 15 < Rutting o si SL < 2 y 2% < Fatigue Cracking ≤ 10%	TMDA<300; 300<TMDA<1200; 1200<TMDA<3000; TMDA>3000			MOP, 2003; MOP, 2006; MOP, 2012; 13 Hicks

Concrete Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
Crack and joint sealing	Rutine Maintenance	Every 2, 3 or 4 years				Manvu, MOP 2003 y 2006; 22 Hicks y NCHRP Peshkin, TAC
Slab repair	Rutine Maintenance	Blow up, durability cracking, moderate deteriorated patch, low/moderate spalling and moderate/high scaling				(Hicks et al. 2000)
Diamond grind	Preservation	IRI > 3,5 or faulting > 3mm Faulting > 4 mm IRI > 4 or faulting > 5 mm IRI > 5 m/Km		Improve IRI to 1,5 m/Km Decrease thickness in 2mm Improve: friction, roughness, service life		MOP, 2003 y 2006; Hicks y NCHRP Peshkin
Asphalt overlay	Maintenance	High long and trans cracking, popouts, moderate/high scaling				(Hicks et al. 2000)
Concrete overlay	Maintenance	High long and trans cracking, popouts, moderate/high scaling				(Hicks et al. 2000)
Drainage improvement	Maintenance	Not Aplicable to urban pavements				
Rehabilitation	Rehabilitation	$p \geq 2.5$ $p \geq 2.0$ $p \geq 1.5$				Manvu

Concrete Pavements						
Maintenance Activities	**Maintenance Type**	**Application Policy**	**Recommendations for Application**	**Effect on ICPU**	**Service Life**	**Reference**
Slab replace	Maintenance	(1) Cracking > 80% (2) Cracking > 50% (3) Cracking > 20% (4) Cracking Index >150	(1) Reemplace of 20% of slab with high deterioration (2) Reemplace of 50% of slab with high deterioration (3) Reemplace of 100% of slab with high deterioration (4) 5% cracked area			MOP, 2003 y 2006
Recycling	Rehabilitation	High long, trans, oblique and durability cracking				(Hicks et al. 2000)
Reconstruction	Rehabilitation	High long, trans, oblique, durability cracking and deteriorated patch				(Hicks et al. 2000)

Appendix J

References of Technical Standards for Chile

References of Chilean Technical Standards for Asphalt Pavements

Type of P&M&R Action	P&M&R Action	Construction Standard
Preservation	Crack Sealing	Article 10.3.2.1 *
	Pothole Repair	Article 10.3.2.2 *
	Fog Seal	Article 10.3.1.1 *
	Slurry seal	Article 10.3.1.3 * Type II aggregate is considered (6)
	Seal Coat	Article 5.9 *
	Microsurfacing	Volume 5 of the Road Manual (MOP, 2014)
	Functional resurfacing	Article 10.3.3.2 *
Maintenance	Hot In-Place Recycling	
	Cold In-Place Recycling	Section 5.413 of the Road Manual (MOP, 2014)
	Structural Resurfacing	Article 5.11
Rehabilitation	Reconstruction	

(*) Code of Norms and Technical Specifications for Paving Work (MINVU, 2008)

References of Chilean Technical Standards for Concrete Pavements

Type of P&M&R Action	P&M&R Action	Construction Standard
Preservation	Crack and joint sealing	Article 9.5.1 *
	Corner Breaks Repair	Article 9.5.5 *
	Diamond Grinding	Articles 9.5.1 *
	Thin Asphalt Overlay	Article 10.3.3.2 *
	Bonded Concrete Overlay	Section 4 *
Maintenance	Crack and Joint Stitching	
	Full-Depth Slab Repair	Article 9.5.5 *
	Structural Resurfacing	Article 5.11*
Rehabilitation	Reconstruction	Section 4 *

(*) Code of Norms and Technical Specifications for Paving Work (MINVU, 2008)

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