Evaluating the Effectiveness of a Pavement

Preservation Program: A Case Study

by

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ABSTRACT

A successful implementation of a Pavement Management System (PMS) allows agencies to make objective and informed decisions in maintaining their pavement assets effectively. Since 2008, the City of Phoenix, Arizona, has implemented PMS to maintain approximately 7,725 km (4,800 mi) of pavements. PMS is not a static system but a dynamic system requiring regular updates to reflect pavement performance and meet the agency's goals and budget. After upgrading to the Automated Road Analyzer (ARAN) 9000 in 2017, there is a need for Phoenix to evaluate its PMS. A low pavement condition index (PCI) for newly paved roads and the requirements for more than 35% of scheduled fog seal projects to be upgraded to heavier treatments observed, also motivated this research effort.

The scope of this research was limited to the flexible pavement preservation program and the objectives are: (1) to evaluate the effectiveness of the existing City of Phoenix PMS and (2) to recommend improvements to the existing PMS.

This study evaluated technical and non-technical aspects of Phoenix's preservation program. Since pavements in a structurally sound condition are good candidates for preservation treatment, a single pavement performance indicator, which allows agencies to be more flexible with their preservation treatments and minimize the pavement performance data collection and modeling efforts, was explored. A simple yet measurable and trackable pavement performance indicator, Surface Cracking Index (SCI), representing the overall pavement condition to perform PMS analysis for a preservation program, was proposed.

In addition, using a performance indicator, the International Roughness Index (IRI) to represent the ride quality or roughness, is a challenge for many local governments due to the nature of urban roadway related conditions such as stop and go driving conditions, abrupt lane change maneuvering, and lower prevailing speed. Therefore, a surface roughness indicator, Mean Profile Depth (MPD) measuring pavement surface macrotexture, was explored, and is proposed to be integrated in the PMS to optimize preservation treatments and recommendation strategies.

While Phoenix will directly benefit from this research study outcomes, any agency who uses PMS, or plans to use PMS for their preservation program, will also benefit from this research effort.

Dedicated to my father (Awa)

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TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF THE CITY OF PHOENIX PAVEMENT MANAGEMENT SYSTEM

Pavements are one of the most expensive assets for the City of Phoenix; the city maintains approximately 7,725 km (4,800 mi) of asphalt concrete pavements. Since 2008, the city has implemented the Pavement Management System (PMS) to assist in prioritizing streets for pavement preservation treatments. PMS provides information to the city's pavement management team to objectively evaluate and prioritize streets for resurfacing based on needs and budgetary constraints, and to determine the most cost-effective treatment strategy to maintain the pavements in their jurisdiction using available funds. The implementation of a reliable PMS allows agencies to make objective decisions, predict the future pavement condition, plan for future needs, perform comparative analysis and reporting, prioritize pavement maintenance activities, and visualize impact of the potential budget increases, cutbacks or alternative work plans today and in the future. There is a need to constantly monitor the PMS and evaluate its effectiveness, for agencies to effectively spend the limited funds available to preserve their pavement infrastructure. On January 1, 2016, approximately $40 million was funded to maintain the city's street network annually; the first fully objective pavement maintenance program to replace the former complaint-driven maintenance program, was developed. Since then, the PMS has been used in developing a multi-year treatment plan and corresponding analysis is being performed annually.

The city's road network comprises major arterial, arterial, major collector, minor collector, industrial, and local or residential streets. Major arterial streets serve long distance travel within the City of Phoenix and between Phoenix and other cities. The major arterial street access is controlled through frontage roads, raised medians, and the spacing and location of driveways and intersections and raised median separates the opposing traffic movement and therefore provides limited service to abutting land. Arterial streets serve a moderately long-distance travel within Phoenix and between Phoenix and adjacent cities. Arterial street access is also controlled through frontage roads, raised medians, and the spacing and location of driveways and intersections. The opposing flow of traffic is separated either by a raised median or a continuous left turn lane and therefore provides moderately limited service to abutting land.

Collector streets serve short distance travel which is less than 4.8 km (3 mi) and are intended to collect and distribute traffic between local streets and arterial streets. Some collector street access may be controlled by raised median and the spacing and location of intersections and driveways, but collector street provides direct access to abutting land. Minor collector streets also serve short distance travel which is less than 4.8 km (3 mi) and are intended to collect and distribute traffic between local streets and arterial streets. Some minor collector street access may be controlled by the spacing and location of intersection, but collector street provides direct access to abutting land. Local street serves local travel providing direct access to residential, commercial, industrial, and other abutting land and connecting to other street classifications. Local streets serving the industrial heavy truck use are classified as industrial streets.

The City of Phoenix street network is categorized into two sub networks: 1) arterial and collector streets and 2) minor collector, local, and industrial streets. A two-person inhouse crew evaluates the pavement condition of the entire pavement network over a two-year cycle: each sub network category in alternate years. A single-pass survey is performed on local streets and minor collectors. To have consistency over the years, on multi-lane arterial and major collector streets, the following drive lane criteria were established: the lane closest to the curb or outside edge of the street for two lane street, the middle lane for the three-lane street, and any lane that is not adjacent to the inside or outside edge of the street for streets with more than three lanes.

The local street network is grouped into Quarter Sections (QS) following a grid system which are typically bounded by minor collector streets; there are nearly 2,000 quarter sections within the city limits. A quarter section is 0.8 km squared (½ mi squared) with an area of 0.65 km^2 (160 acres). The city has identified quarter sections with a numbering system giving each a unique number. For example, QS10-27 where QS stands for quarter section, the first two numbers represent a vertical location, while the last two numbers represent a horizontal location. Minor collector, major collector, and arterial street sections typically run for distances of about 0.8 km (½ mi) in one direction. It is impractical, from a construction perspective, to have different pavement treatment types for streets every 0.8 km (½ mi) section and for opposing traffic lanes. Therefore since 2012, the 0.8 km (½ mi) adjacent collector or arterial street sections are grouped into 1.6 km (1 mi) Super Section (SS) based on their pavement condition and street classification. For example, there would be two arterial street sections for McDowell Road between 7th Avenue and 15th Avenue, one for the eastbound lanes and one for the west bound lanes. The adjacent section, McDowell Road between 15th Avenue and 19th Avenue, would also have two street sections, one for the eastbound lanes and one for the west bound lanes. A super section combines four adjacent arterial and major collector street sections into one super section. As for the minor collector, which is typically a two-lane two-way street, a super section comprises two sections. For example, 87th Avenue between Lower Buckeye Road and Durango Street is a 0.8 km (½ mi) section and 87th Ave between Durango Street and Buckeye Road is a 0.8 km (½ mi) section. They are combined to form a 1.6 km (1 mi) super section.

In August 2008, to objectively assess pavement condition, the City of Phoenix replaced visual inspection with Automated Road Analyzer (ARAN) III equipped with two pavement cameras and two Laser South Dakota Profilometers (SDP) to automatically analyze cracks on pavement and to measure longitudinal profiles. Distresses collected are cracks and the International Roughness Index (IRI). Other distresses such as bleeding, raveling, and rutting require manual intervention, the rater keying in a code when these distresses are observed. In December 2017, the city upgraded to ARAN 9000 model, a fully automated advanced pavement data collection van, to better detect and analyze cracks and automatically detect additional distresses including macrotexture, bleeding, raveling, and rutting.

Along with ARAN III, the city purchased distress extraction software, Vision software, developed by Fugro Roadware to process and analyze the data acquired by the ARAN. One of the key elements of the Pavement Management System is the ability to quantify the amount, and type of cracking present on the roads. Vision software processes the collected images of the roadway surface to classify the type, rate the severity, and quantify the amount of cracking and prepares this data for export to PMS analysis software and eventually programs the streets for maintenance.

While Fugro's Vision Processing Software is used to process pavement condition data, Deighton Associates' PMS analysis software, Deighton's Total Infrastructure Management Software (dTIMS), is utilized to manage all aspects of the City's pavement management. One of the main functions of dTIMS is to analyze the pavement distress data from Vision to determine appropriate pavement preservation treatments for the future. Typically, pavement condition data collected is used for programming five years out in the future. Information generated by PMS software is used to evaluate and prioritize streets for treatment based on pavement condition, budget, and utility conflicts.

Factors such as environmental and soil conditions affect the performance of flexible pavement over time. Phoenix is classified as hot, dry areas characterized by the maximum temperature of greater than 32°C (90°F) and rainfall rate less than 250 mm (9.84 in) annually (Hozayen & Fouad, 2015). The average daily temperature in Phoenix is about 24°C (75°F) while the minimum temperature is −1°C (30°F). The lowest recorded temperature was −9°C (16°F) and the highest recorded temperature was 50°C (122°F). Phoenix region also experiences high temperature fluctuation with a daily summer hot and dry temperature ranging from 32.2°C (90°F) to 48.9°C (120°F) and in the winter from 4°C (39°F) to 19°C (66°F). As shown in Figure 1-1 from Natural Resources Conservation Service (NRCS), expansive soils also referred to as "shrink/swell" or "shrink-swell" are scattered in arid Phoenix area. The soil with high shrink/swell potential is shaded in red, moderate in yellow, and low in green respectively. Attributing much to the environmental condition in Phoenix, the predominant distresses observed historically and at the present time are cracking, rough texture, and rutting.

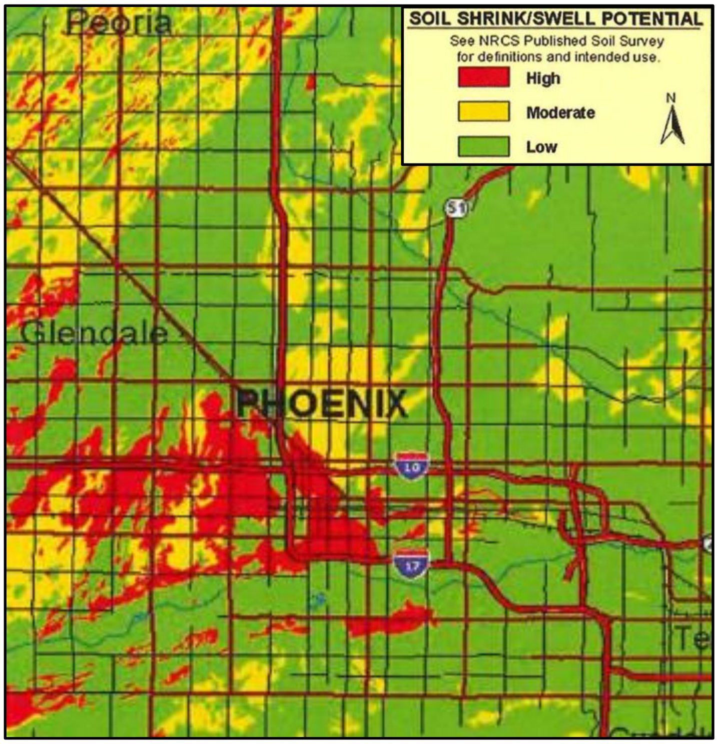


Figure 1-1: Phoenix Area Soil Map from Natural Resources Conservation Service (NRCS)

To address pavement distresses specific to the City of Phoenix, its maintenance and preservation pavement surface treatment toolbox includes edge mill and thin overlay, micro seal, slurry seal, Fractured Aggregate Surface Treatment (FAST), fog seal such as OptiPave and seal coat such as Liquid Road. Each of the primary treatments receives crack seals as a preparatory treatment. Projects programmed for an overlay treatment also receive the opportunity to upgrade sidewalk ramps to meet the minimum requirements of the Americans with Disabilities Act (ADA) and reconstruct existing damaged valley gutters or installation of valley gutters to provide positive flow. Although not common, when safety is a concern, full depth pavement reconstruction and soil stabilization to provide structurally sound pavement is recommended at a project level assessment. With a good PMS in place, the expectation is the extension of the life of asphalt pavement from 25 to 30 years, and even up to 40 years, saving taxpayer money while providing safe and efficient roadways.

1.2 RESEARCH MOTIVATION AND OBJECTIVE

The success of the pavement management system is dependent on collecting reliable pavement condition data to capture major distresses observed in the City of Phoenix. Distresses typically observed in urban areas can be grouped into three main distress types: surface cracking, surface texture, and surface deformation. With the poor subgrade soil condition and extreme hot and fluctuating temperature conditions, pavements in the Phoenix area age faster and experience contraction and expansion, accelerating pavements to crack. Even the most extensive maintenance and preservation treatment option, thin overlay, can last just a few months before hairline reflective cracks are observed. As shown in Table 1-1 below, greater than 35% of fog seal locations recommended and programmed to receive fog seal three years ago became obsolete since pavement deteriorated faster than forecasted. Based on field reassessment performed by pavement engineers in June 2020, of 180.26 km (112.01 mi) of the fiscal year 2021 programmed fog seal treatment locations, 45.77 km (28.44 mi) would need to be upgrades to 37.16 km (23.09 mi) to seal coat, micro seal/slurry seal, 2.62 km (1.63 mi) to FAST, and 15.47 km (9.61 mi) to thin overlay.

Table 1-1: Results from the Reassessment of Fiscal Year 2021 Programmed Fog Seal Projects for Treatment Recommendation

	Based on Treatment Recommendations from June 2020 Field Review					
	Fog Seal	Seal Coat	Micro seal/ Slurry Seal	FAST	Thin Overlay	Total
Programmed Fog Seal	79.24 km (49.24 mi); 43.96%	37.16 km (23.09 mi); 20.61%	45.77 km (28.44 mi); 25.39%	2.62 km (1.63 mi); 1.46%	15.47 km (9.61 mi); 8.58%	180.26 km (112.01 mi); 100%

Phoenix spends approximately $40 to $50 million annually on its flexible pavement maintenance and preservation program to treat between 483 to 563 linear km (300 to 350 linear mi) of streets. Therefore, in order to properly manage pavement assets in Phoenix under stringent budget and sparse maintenance, the quality of the PMS from data collection to the analysis, to programming must be in check. Thus, the main objectives of this research study are to evaluate and improve the existing City of Phoenix PMS and evaluate the effectiveness of implemented PMS.

1.3 RESEARCH APPROACH

Since its inception in 2008, City of Phoenix has performed data collection and pavement condition analysis and forecasting in-house to assist in developing optimal pavement maintenance treatment plans based on the available budget. An evaluation of the effectiveness of the pavement preservation program was accomplished by conducting the following tasks:

1. Perform literature review and gain a better understanding on current PMS practices;
2. Review and update road inventory data such as updating maintenance history, adding new road sections, retiring abandoned sections, and redefining road sections and super sections;
3. Explore and evaluate ARAN's pavement condition data collection technology;
4. Select distresses to represent pavement surface condition prevalent in the City of Phoenix;
5. Update distress schema to properly classify and rate distresses;
6. Formulate deduct values, individual distress index, and pavement condition index;
7. Recommend treatment triggers for preservation treatments;
8. Evaluate treatment resets based on treatment design life supplied by the vendor and actual performance of each treatment type;
9. Update treatment unit cost by treatment and street classification;
10. Develop and validate pavement performance models;
11. Evaluate and validate PMS treatment recommendation with field assessed treatment recommendation; and
12. Conduct statistical analysis and evaluate the effectiveness of the PMS.

Figure 1-2 depicts the workflow chart of the above-mentioned tasks which are adopted to achieve the research objectives to improve the current City of Phoenix PMS and evaluate the effectiveness of the PMS.

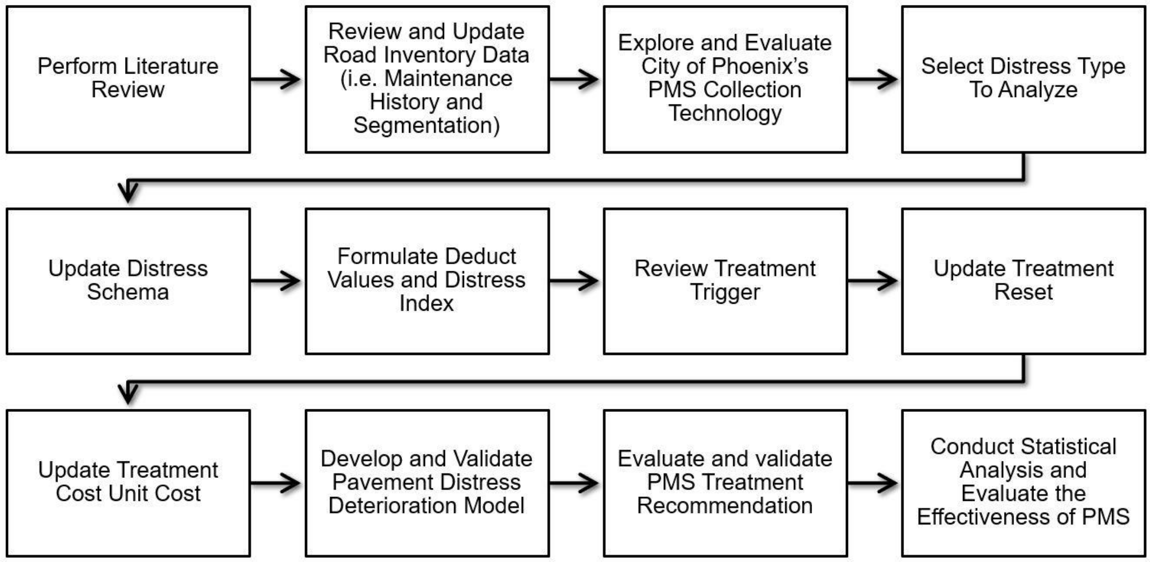


Figure 1-2: Research Approach Workflow Chart

1.4 RESEARCH CONTRIBUTION

Maintaining pavements in an acceptable condition is not a new concept and PMS has been around since the late 1960s. Transportation agencies implemented PMS to help them select the right treatment to be applied to the right road at the right time. A periodic quality check of the pavement condition data collected and reevaluation of the PMS parameters, such as pavement performance prediction models, pavement treatment triggers or treatment reset values are paramount to the successful implementation of PMS.

While the City of Phoenix will directly benefit from this research study outcomes, nevertheless, any agency who uses PMS or plans to use PMS will also benefit from this research effort.

A significant amount of research has been conducted to address PMS processes at the network level for local municipalities. This research offers enhanced PMS concepts on quantitatively measuring how the environmental condition and pretreatments impact pavement performance. The effectiveness of various maintenance, preventive, and rehabilitation treatments addressed in this research study are beneficial to transportation agencies who aspire to ensure that public tax dollars go as far as possible. The research outcomes presented will allow them to discontinue treatments that are not performing well, or simply adjust the treatment cycle. The social benefit for the public is that roadway users will drive on roads in better condition and will encounter less construction delays during their daily commutes.

Many transportation agencies currently contract consultants to perform PMS data collection and analysis work. This means, when the contracted service term is over, there is a greater chance for a change in the data collection process and analysis methodology. Moreover, with technology changes, such as upgrades from manual survey to 2-D to 3-D data collection technology, Pavement Condition Indices (PCI) may be inconsistent. Therefore, the proposed simple pavement evaluation method for the pavement preservation program will be beneficial to agencies in the long-term. Due to the ARAN 9000 hardware limitation, the quality and configuration of an inertial profiler's accelerometer, IRI is abnormally high and not valid when the vehicle operating speed reaches below 25 km/h (15 mph) (Gumisiriza, Li, & Lee, 2018), (Fugro Roadware, 2019), and (Howard, 2013). The portion of the research on pavement surface macrotexture may be better suited for pavement surface roughness.

1.5 DISSERTATION ORGANIZATION

This dissertation has been divided into eight chapters. Chapter 1 covers an overview of the City of Phoenix pavement management system, dissertation research motivation and objectives, research approach and research contributions. Chapter 2 provides a literature review on the pavement management system and pavement surface texture. Chapter 3 covers an evaluation of the City of Phoenix's technical and non-technical components of PMS. Chapter 4 presents a simplified method of assessing pavement condition to make network level PMS decisions for preservation treatment options. Chapter 5 explores various types of pavement condition assessment methods: Phoenix's ARAN collection method, ASTM manual survey method, windshield survey method, and an additional vendor's method who approached the City of Phoenix during this research study. Chapter 6 covers pavement surface macrotexture and presents the macrotexture index to use as a performance indicator for PMS analysis. Chapter 7 covers pavement preservation treatments in the City of Phoenix toolbox, and their effectiveness in mitigating pavement surface distresses. Chapter 8 concludes with a summary of findings, conclusions, and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Since its implementation in 2008, the City of Phoenix has not evaluated the effectiveness of its Pavement Management System. Recently the city upgraded to an automatic road analyzer that is equipped with the Laser Crack Measurement System (LCMS) which is capable of measuring macrotexture automatically at the speed of traffic. This new capability promises the possibility of using macrotexture measure to replace roughness index predecessor, IRI. The objectives of this literature review are to gain an understanding of how to properly evaluate the efficiency of the city's pavement management system and to gain an insight to how the pavement surface roughness can be used as a pavement performance indicator. A review of previous research work to answer the questions encountered during the dissertation research effort is documented in this chapter. The chapter is divided into two major sections: the first section presents pavement management systems, and the second section presents pavement surface roughness.

2.2 PAVEMENT MANAGEMENT SYSTEM

2.2.1 Overview of Pavement Management System

Pavement management system is a set of activities, or a system of approaches agencies employed to assist decision makers and upper management in making informed, consistent, cost-effective, and defensible decisions to provide, evaluate, and maintain serviceable and safe pavements in their network (AASHTO Executive Committee 1989, 1990). Although PMS cannot perform the final engineering or management decision, it can provide insights to the possible consequences of alternative strategies so agencies can make informed decisions and assist in selecting the most cost-effective treatment strategy, prioritize treatment locations, program treatment timing, project funding needs, and identify problem areas. PMS can provide general and specific pavement information required to generate defensible funding needs for decision-makers and upper management to communicate with the legislature and the public.

A comprehensive PMS includes modules to assist in making both network and project level decisions (AASHTO Executive Committee 1989, 1990). The network level decisions involve identifying and setting priorities, establishing budget, allocating funds, and scheduling maintenance, rehabilitation, and reconstruction (MR&R) for an entire network. At a minimum, PMS is to provide pavement condition data, MR&R treatment strategies, estimates of funding needed to achieve a target level of network performance, and priority listings of projects to execute network level decisions. The project level decisions involve addressing engineering and technical aspects of pavement management such as the selection of a site-specific MR&R actions for individual projects and groups of projects and estimating the project costs and expected life. Thus, in addition to the data required to perform network level decisions, project level PMS requires detailed site-specific information such as condition survey, material properties, and drainage condition to prepare final design plans, specifications, and cost estimates for the MR&R treatments.

A typical basic PMS covers three modules: database, analysis method, and feedback process (AASHTO Executive Committee 1989, 1990). A database contains information such as pavement section location, length, width, functional classification, pavement type and material, current and historical pavement condition, construction, maintenance, and rehabilitation history, cost data, traffic condition, climatic condition, drainage condition, soil condition, and others. In addition to supplying the information needed to support the other two modules, information in the database can be used to analyze and compare pavement sections for deficiency, to establish strategies to trigger pavement preservation and rehabilitation treatments, to program the most cost-effective and beneficial sections for treatments, to monitor pavement performance over time, and to report pavement inventory or pavement condition based on the severity and extent of specific types of distresses (Pierce, McGovern, & Zimmerman, 2013) (AASHTO Executive Committee 1989, 1990).

A variety of analysis methods are available and can generally be grouped into three categories: pavement condition analyses, priority assessment models, and network optimization models. Pavement condition analysis combines individual pavement distress data with or without roughness to generate a single overall pavement condition score or index to rank the health of the pavement sections within the network, to identify MR&R strategies, and to estimate funding needs. While the pavement condition prediction model is not necessary to perform pavement condition analysis, priority assessment models and network optimization models incorporate performance prediction models. The priority assessment models use the optimal benefit/cost ratio and cost effectiveness strategy approach to generate a priority listing of individual projects for a single or multi-year MR&R program and to estimate cost for MR&R treatments and the funding needed to achieve the target network performance level over an analysis period. Although the output generation capabilities are essentially the same as the priority assessment models, the network optimization models determine the optimal network MR&R strategies by maximizing the total network performance benefits or minimizing the total network cost to achieve the desired performance standards.

A feedback process is a continuous process performed to improve the reliability and make PMS analysis credible by comparing the actual costs of MR&R, treatments applied, and pavement performance after treatment with those in or recommended by the PMS analysis. Furthermore, the feedback process allows the agency to evaluate the effectiveness of the treatment plan and research the influence of changes in material properties, construction practices, and/or design procedures on the long-term performance of pavement after application. Finally, feedback allows the agency to further improve the models used to trigger sections for treatments.

2.2.2 Pavement Condition Data

A critical component of a pavement management system is the pavement condition data (AASHTO, 2012). While there are many different types of data that may be collected, they can be characterized into three main categories: distress, surface characteristics, and structural capacity. Since distress is the visible defect that either directly indicates the cause of pavement performance problems or the underlying problems, distress information is used in selecting, planning, and programing specific pavement preservation and rehabilitation treatments. Surface characteristics related to the pavement longitudinal profile or smoothness and pavement surface texture affect the ride, friction, and noise. Although a pavement may be free from major distress and exhibit adequate structural capacity, its surface characteristics affecting the safety and comfort of roadway users may warrant surface treatment to improve rideability and reduce friction related crashes. Structural capacity is the ability of a pavement to carry load and is evaluated by measuring the pavement's response to applied loads. Data from structural evaluation is used to assist in identifying structural problems by providing indirect measurements of intrinsic strength/stiffness properties, as well as prioritize rehabilitation needs and treatment strategies. While distress and pavement longitudinal profiles are collected as part of a network-level pavement condition survey typically, surface texture and structural capacity are collected as part of a project-level PMS (AASHTO, 2012).

Visible pavement distresses are identifiable and quantifiable pavement defects which emerge as pavements age and are exposed to environmental and traffic loadings. Visible distress surveys measuring, and cataloging distress type, severity, and extent are performed as part of a pavement condition survey. Since agencies developed their own pavement distress identification manual to more accurately reflect their local pavement network, available treatment or maintenance resources, and distress data collection technology, the distress data collected and reported lacked consistency between agencies. Although there is not a single correct approach to distress data collection, two manuals describing pavement distress in detail were developed to foster a more uniform and consistent definition of pavement distress and thus assist agencies and researchers to collect pavement performance data in a consistent and repeatable manner irrespective of the raters and collection methods. They are the FHWA's Distress Identification Manual for the Long-Term Pavement Performance Program (Miller & Bellinger, 2014) and Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys (ASTM D6433-20, 2020). The distresses, severity levels (low, moderate, and high), and how to measure and report distresses are defined and supplemented with illustrations in the manuals. Table 2-1 provides a list of flexible pavement distresses collected and Table 2-2 provides the causes of each distress type.

Table 2-1: Summary of Asphalt Pavement Distresses Defined in Distress Identification Manual for The Long-Term Pavement Performance Program and Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys

Distress Identification Manual for The Long-Term Pavement Performance Program	Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys (ASTM D6433)
1. Fatigue Cracking	1. Alligator cracking (fatigue)
2. Block Cracking	2. Bleeding
3. Edge Cracking	3. Block cracking
4. Longitudinal Cracking	4. Bumps and sags
5. Reflection Cracking at Joints	5. Corrugation
6. Transverse Cracking	6. Depression
7. Patch/Patch Deterioration	7. Edge cracking
8. Potholes	8. Joint reflection cracking
9. Rutting	9. Lane/shoulder drop-off
10. Shoving	10. Longitudinal and transverse cracking
11. Bleeding	11. Patching and utility cut patching
12. Polished Aggregate	12. Polished aggregate
13. Raveling	13. Potholes
14. Lane-to-Shoulder Dropoff	14. Railroad crossing
15. Water Bleeding and Pumping	15. Rutting
	16. Shoving
	17. Slippage cracking
	18. Swell
	19. Weathering and raveling
	20. Ride quality (evaluated to establish a severity level for the following distress types: bumps, corrugation, railroad crossings, shoving, and swells.)

Table 2-2: Common Causes of Flexible Pavement Distresses

Distress Type	Traffic/Load	Climate/ Materials
Fatigue Cracking	x	
Block Cracking		x
Longitudinal Cracking	x	x
Transverse Cracking		x
Patch/Patch Deterioration	x	
Potholes	x	
Rutting	x	
Shoving	x	
Bleeding		x
Polished Aggregate	x	
Weathering and Raveling		x

For the pavement management purpose, network level surveys that are less detailed than project level surveys and conducted on the majority, if not all, of the agency's pavement network are sufficient (AASHTO, 2012). Pavement distresses that are prevalent in one area may be trivial in others because factors including the pavement structural design, climate, traffic, materials, subgrade, and construction quality contribute to the variability in the pavement behavior and performance and are reflected in pavement condition survey ratings. At the network level, agencies collect common asphalt pavement distresses such as load and non-load related cracking, shoving or distortion, potholes and/or patching, bleeding, raveling, polishing, and roughness annually or every 2 to 4 years. Less common pavement condition data collected are pavement friction, structural capacity, and macrotexture (Pierce, McGovern, & Zimmerman, 2013).

The quality of pavement management decisions is a function of the data available and there is a direct link between data needs and decision-making. Agencies must balance between collecting more detailed condition data at a higher cost and collecting sufficient data to confidently make good decisions because data quality, data quantity, and data consistency are important considerations in data collection. Moreover, an accurate and up to date representation of pavement condition data is necessary to support effective network level decision. Therefore, agencies must first identify the exact information required to support their key decisions and consider resources available to perform pavement data collection regularly before selecting the most effective methods of collecting the data (AASHTO, 2012).

The results of a network-level survey are most used to identify and prioritize treatment needs, to determine funding needs, and to allocate budgeted funds (Pierce, McGovern, & Zimmerman, 2013). A summary of an agency's pavement network conditions provides valuable insights on current pavement preservation and rehabilitation needs. Perhaps even more importantly, over time the regular collection of current conditions generates a historical record of the progression of pavement condition, and the collected information can be used to model and predict future conditions. Hence, the results from the pavement condition assessment provides the inputs required to describe current pavement performance, to track pavement performance over time, and to predict pavement conditions in the future (both with and without the application of treatments).

Another important aspect of collecting pavement distress information for agencies to decide is whether to inspect the entire pavement network in their jurisdiction or a representative sample section of pavements. For example, ASTM D6433 standard recommends inspecting at least 10% of the pavement network and the minimum distress measuring sample unit of 225 m^2 (2,500 ft^2) for asphalt concrete pavement. There are three primary pavement condition assessment methods. The first method, the manual survey method, is conducted by walking or traveling at slow speed rating surface distress and recording on paper, computers, or handheld devices. The second method, the automated survey, is conducted by van and data captured by the video and/or laser technology is processed fully automated. The third method, the semi-automated survey, makes use of both automated and manual survey methods. The data is collected using automated equipment while the captured distresses are manually processed by trained personnel (Pierce, McGovern, & Zimmerman, 2013).

One of the most difficult decisions agencies face when collecting pavement condition data for an extended period is changing survey method or distress rating protocol. The growing pavement network in the jurisdiction, the needs for objective rating, the concerns for the raters' safety, the increased use of performance measures reflecting strategic performance measure (i.e., treatment sustainability) and the complexities in analyzing large data in a limited time may prompt agencies to change their pavement condition survey procedures to reflect changes in technology. An upgrade in the survey technology requires a modification in the distress rating process, usually to account for the new technology capabilities. When these changes are inevitable, instead of wasting time preserving obsolete historical data and attempting to try to correlate the old data with the new data that are drastically different, dissociating from the historical data is more practical (AASHTO, 2012). The Pavement Management Guide suggests agencies rebuild a new set of historical data after adopting the new survey procedure by recognizing the inherent variability from different survey procedures and accepting the differences in the data being reported. The obsolete historical data collected by the old survey procedures can still be used to determine the general pavement deterioration trends.

The method to determine distress severity can be very resource and labor intensive. The agency may need to resort to estimating distress quantities and accepting subjectivity and variability. As pavement data collection technology evolves rapidly, technological advancement improves data quality. On the other hand, as the technologies evolve and new data are collected with the added capabilities, continual updates of pavement performance curves, treatment triggers, and condition reporting are required to address the data inconsistency issues. Irrespective of data collection methods, an effective pavement management system depends on high quality network-level pavement condition data that is reliable, accurate, and complete to perform reasonable, timely, and reliable analyses for pavement management purposes. Agencies can achieve the right balance of data quality and added effort, time, and budget by reflecting on the intended use of the pavement condition data. Although it is challenging, an important aspect to an evaluation of the data quality which correctly reflect the conditions in the field with a low error is to establish reference values or “ground truth” at control and blind sites for all distresses or pavement condition to be collected (Pierce, McGovern, & Zimmerman, 2013).

Irrespective of the survey methods, pavement condition information collected is primarily used to report network condition, rank pavement sections, trigger treatments, predict future conditions, and establish the rate of pavement deterioration. Therefore, transforming raw distress data collected into meaningful information that meets the needs of the agencies is crucial. The raw pavement condition data measuring various distresses and severities are converted into two main types of condition indices: individual indices or composite indices.

Individual indices consider a single distress type such as fatigue cracking or distress category such as structural cracking and are used in recommending treatment and calculating the composite index. An individual index can be calculated by applying the deduct point concept from a perfect score or using actual collected values such as International Roughness Index (IRI) value. Individual indices allow agencies to quickly identify the most appropriate type of maintenance and repair activity. However, the use of multiple individual indices for treatment selection adds complexity by requiring agencies to develop treatment rules for each individual index and performance models for each individual index by pavement surface type. For example, three surface types and two individual indices will involve developing six different performance models. Agencies typically use individual indices in conjunction with the composite index. The Pavement Management Guide suggested developing the performance models for individual indices first and then calculating the composite index, to eliminate the possible discrepancy between the predicted composite index and the predicted individual indices.

Composite index is a single index that integrates multiple distresses to represent the overall condition of a pavement and commonly used in rating pavement condition descriptively (i.e., good, fair, or poor) and comparing the conditions of the sections. The composite indices can be a subjective rating of the pavement by the rater such as the Pavement Surface Evaluation Rating (PASER) condition survey procedure for asphalt roads developed by the University of Wisconsin (Wisconsin Transportation Information Center, 2002). PASER is a “windshield” rating system with values ranging between 1 and 10 where 1 represents failed pavements requiring a total reconstruction, and 10 represents a new pavement in excellent condition requiring no maintenance. The subjective rating method of assigning a condition index is quick and simple to perform. Although the subjective composite index provides useful information to agencies without extensive resources for data collection, they do not provide information on the types and amount of distress observed and can be highly subjective generating substantial variability between index values from year to year or even between experienced raters for the same year for the same pavement section.

The objective composite rating is a more complex and objective measure of various distresses, severity, and extent such as pavement condition index (PCI) developed by the U.S. Army Corps of Engineers (ASTM D6433-20, 2020). PCI is a “knee and elbow” rating system with values ranging between 0 and 100 and depending on the combination of distress type, severity, and extent observed in the field deduct values provided by the deduct curves in ASTM D6433 are summed, adjusted, and deducted from the perfect score of 100. Typically, more points are subtracted for structural deterioration such as severe fatigue cracking than for less serious distress such as weathering. Compared to subjective composite indices, objective composite indices are more labor intensive but provide agencies with a greater detail on the percent of specific types of distresses which may be useful when estimating maintenance and repair activities.

2.2.3 Pavement Performance Model

The pavement performance models depicting the changes in pavement condition over time are also known as the pavement deterioration models or pavement performance prediction curves. The pavement performance models address the agency specified goals, objectives, and constraints by accurately estimating the future condition of the pavement, determining the most cost-effective treatment strategy at an appropriate timing, evaluating the effectiveness of different maintenance and investment strategies, and estimating the Remaining Service Life (RSL). RSL for a pavement section is the shortest number of years remaining until an agency-defined minimum service level, or threshold level is reached. Since pavement performance models are developed for specific intended purposes, the data requirements in developing reliable and accurate performance models should consider the data availability over time, the important variable(s) impacting pavement performance, and the form of data reflecting a typical pavement deterioration pattern (AASHTO, 2012).

The performance models may be modeled to predict changes in these three variables: the distress severity and extent, individual indices, or composite indices over time. The models to predict changes in the distress severity and extent resemble the collected distress data format in the closet but are the most complex and difficult to incorporate into the pavement management software. The models to predict the composite indices are the simplest to modeling approach but can be difficult to accurately predict changes in composite indices because of the number of combinations of distresses that can result in the same value. The models to predict individual indices are easier to model than distress severity and extent but require developing models for multiple individual indices to trigger treatments.

Depending on the variables used for modeling, the model may be constructed based on the mechanistic, empirical, or mechanistic-empirical approaches. The mechanistic model is based on the fundamental principles of pavement behavior. The empirical model is based on the results of the experiments or experience. The mechanistic-empirical models which are commonly used in pavement management are based on both approaches and relate the predicted condition to measured deterioration.

The pavement performance model described in mathematical expression can follow one of the four approaches: deterministic, probabilistic, Bayesian, and subjective. The deterministic models may be represented by a linear, quadratic, or sigmoid equation to predict a single dependent variable such as pavement condition by using independent variable(s) such as pavement age or traffic volumes. Agencies need historical pavement condition data or sufficient survey data for at least one independent variable to derive pavement deterioration trends by performing statistical regression analysis in developing deterministic models. Probabilistic models use either Markov or Semi-Markov probabilistic approaches. Based on the current pavement condition and by directly accounting pavement variability, probabilistic models predict the probability of a pavement changing from one condition state to another, thus are particularly useful for predicting individual distress information. Since Bayesian models can be developed using only subjective data, subjective data supplemented by objective data, or both objective and subjective data, they allow agencies to override missing historical data, insufficient data, or poor data and supplement with the expert opinion models until data become available to improve the prediction models. Bayesian models use multivariate regression analysis, and the variables used in the models are assumed to be random and have associated probability distribution. Although similar to deterministic models, subjective or the expert-based models use expert subjective opinions to establish the relationships between independent and dependent variables and to develop equations that describe the rate of deterioration instead of historical data.

Each of the four performance model approaches can be used to develop deterioration rates for site-specific or pavement family models. Site-specific models represent the unique characteristics of a particular pavement section to predict future conditions while pavement family models represent the rate of deterioration for a group of pavement sections with similar performance characteristics. Most agencies require at least three to five historical condition data points be available after pavement construction or treatment for the pavement section before site-specific models can be used. Pavement families can be established very simply by grouping pavement sections by their surface types or quite complex by a combination of geographic location, surface type, functional classification, and freight volume. The family modeling approach simplifies the modeling process by reducing the number of independent variables in the performance model to a single independent variable such as pavement age or traffic to predict future pavement conditions. Since a single-family model represents average rates of change for several pavement performance curves for all sections that fit the family, it is highly likely that many of the actual data point from the pavement condition survey will not coincide the family model and thus the family model must be “shifted” over to intersect the actual data point. The “shifting of the curve” allows a reasonable prediction of the condition of the section by reflecting the general deterioration trend of the family model while tailoring the family model for each individual section.

Since most of the initial pavement performance models are developed using the expert opinions, as the data from the pavement condition survey become available, it is important to incorporate the actual data into the models. Moreover, when the pavement management system is initially implemented, the models need to be reviewed frequently until the initial models are finalized. Thereafter, the models are reviewed periodically to help ensure that they continue to reflect actual pavement deterioration characteristics. Once models are verified, dramatic changes to the models are expected only when changes to the condition rating procedures or condition indices are made, winning the confidence of the stakeholders in the system over time. The reliability, the “goodness of fit”, or the degree to which the predicted models fit the data can be evaluated using statistical methods such as the coefficient of determination (R^2), the Standard Error of Estimate, residual plots, root mean square error (RMSE), t-test, and f-test.

2.2.4 Treatment Recommendation

An application of the right treatment at the right time in the right manner can extend pavement service life (AASHTO, 2012). Pavement management system is used to identify treatments needed to address the current and future pavement deficiencies. Using the performance models to project the pavement condition, the current and future pavement preservation needs and the impacts of different treatment choices on long-term health of the network can be evaluated. In order to be able to recommend either the current or future treatment needs, the agencies must define the types of treatments to be considered to address various forms of pavement deficiencies, establish the conditions under which each of the treatments is deemed appropriate, and project future improvements in condition after treatments.

AASHTO "Pavement Management Guide" describes a broad range of treatment categories available to address pavement deficiencies including pavement reconstruction, pavement rehabilitation, preventive maintenance, routine maintenance, and corrective maintenance. Pavement reconstruction involves a complete removal of the existing pavement structure and replacement by an equivalent new pavement structure. Pavement rehabilitation involves adding or replacing material in the existing pavement structure to reverse and reset the effect of deterioration in the existing pavement. While major rehabilitation such as full depth repair improves the structural capacity of the existing pavements, minor rehabilitation such as thin overlay restores the functional characteristic of existing pavement and the structural capacity to a limited extent. Preventive maintenance involves planned application of cost-effective treatments such as seal coats, micro seal, and crack filling/sealing to existing pavement in good condition. Preventive maintenance improves the pavement functional characteristics by providing users a safe and comfortable ride while it does not significantly increase the structural capacity to withstand traffic and environmental loadings. Routine maintenance involves planned activities such as crack filling or reactive activities such as pothole patching performed by in-house personnel on a routine basis to maintain, preserve, or restore pavements to a satisfactory level of service. Since corrective maintenance involves reactive activities to fix defects that may negatively impact the safety and operations of the pavement section, it may be performed at any time during a pavement's life.

Beside identifying the feasible treatment triggers and their associated costs, defining the reset values or impact rules, the prediction of the future conditions after treatments, is essential for a pavement management analysis. Reset value does not alter the data in the pavement management database but must be developed for both pavement surface type and condition and change in surface type must be updated manually in the database after treatment. The surface type reset rule ensures the appropriate pavement performance model is used for predicting future condition when a change in pavement surface type occurs such as from concrete surface type to asphalt surface type after an asphalt overlay. The condition reset values indicating an update in the condition after treatment are more difficult to establish for preservation treatments than rehabilitation and reconstruction activities. While rehabilitation and reconstruction activities are not affected by the pretreatment condition and revert all condition indices back to a perfect condition, the condition reset values for preservation treatments are affected by the pretreatment condition and improvements may be a certain number of points for an index or negligible for another index. For example, crack sealing may hold the existing pavement condition for a period of time and then resume the pretreatment rate of deterioration. Therefore, reset values are necessary in the pavement analysis for comparing the long-term impacts of one strategy with another and identifying the most cost-effective strategy. However, the use of composite indices rather than individual indices and missing indices, such as surface texture characteristics that trigger the use of these treatments, from the network level pavement condition survey pose a challenge in developing treatment rules for preventive maintenance.

In general, few agencies have sufficient funds to address the needs of their pavement network with the treatments identified and recommended by the pavement management analysis. Thus, agencies rely on their pavement management systems to assist in determining the most cost-effective way to use their limited budget. Agencies have the option to perform analysis for a single year, for multiple years, or for the life of the pavement. A single-year analysis or annual analysis refers to the project and treatment selection process where the selection for the first year is identified first before analyzing for the second year. A multi-year analysis is preferred over a single-year analysis since it allows agencies to develop the optimal project and treatment strategy for each year by considering all the needs in each of the analysis years together. A life-cycle cost analysis (LCCA) considers both costs to the agency such as costs associated with the construction, maintenance, and rehabilitation of the pavement and costs to the roadway users such as construction delays experienced by the users over the analysis period. LCCA allows agencies to compare the cost-effectiveness of various pavement treatment strategies by projecting the costs incurred at maintenance and rehabilitation schedules throughout the analysis period and converting the future cost to a present or baseline period.

There are three analysis approaches with different complexity that can be used in the selection and prioritization of the projects for treatments including ranking, optimization, and heuristic analysis. These three analysis approaches provide a method for identifying an optimal strategy for preserving the condition of the network under constraints such as funding. The network optimization analysis considers the needs and constraints of the network as a whole and collectively. Thus, the optimal strategy reflecting the best strategy for the network, may or may not reflect the best strategy for each pavement section.

Ranking, also known as the worst-first strategy, is one of the easiest and most common approaches. This approach prioritizes the needs and ranks projects based on agency specified priority, such as pavement condition. Since the ranking method does not typically consider the alternative strategies nor the cost effectiveness of alternative strategies to optimize the use of available funding and treatment timing, it is not an appropriate strategy to manage pavement for long-term use.

Optimization is a more complex and computationally demanding approach that uses mathematical models to define the objectives (network condition) and constraints (budget) using mathematical terms. Optimization analysis can incorporate risk, the likelihood of a pavement in one conditional state to move to another, using transition probability matrices developed based on either historical data or expert opinion. Optimization is a two-step process conducted to develop improvement program recommendations which consider trade-offs between different project timings and the impacts on pavement performance over multiple years. The network level optimization analysis reporting the distance or percent of road network to be moved from the current condition state to another condition state through the recommended treatment strategy is conducted first. Then the second analysis is performed identifying the specific project locations and appropriate treatments.

Heuristic analysis techniques such as incremental benefit-cost ratio and marginal cost-effectiveness analyses provide near optimal project and treatment recommendations by considering and forecasting the impacts of treatment timing, treatment options, and the funding levels over multiple years. The incremental benefit-cost ratio approach involves evaluating the marginal improvements on long-term network pavement condition with the application of treatments or the additional investments in terms of benefit while the marginal cost-effectiveness approach involves evaluating in terms of the effectiveness.

2.2.5 Integrating Preservation Treatments in PMS

Pavement preservation uses a proactive approach in maintaining pavement assets and consists of both preventive maintenance and minor rehabilitation. Federal Highway Administration (FHWA) describes preservation as a critical component of an agency's network level asset management plan performed to improve or sustain the condition of the transportation facility in a safe state of good repair without adding capacity or structural enhancement (Waidelich Jr., 2016). Many agencies realized that preservation offers a low-cost method of preserving the pavements early in the life of the pavement life cycle and deterring pavements from deteriorating to the condition requiring very expensive reconstruction or rehabilitation activities. Therefore, agencies are choosing to incorporate pavement preservation activities in their overall maintenance and rehabilitation analysis framework. Pavement preservation treatments have unique capabilities and are intended to be preventive, restorative, or corrective to a limited extent when applied on pavements that are in relatively good condition and have little or no structural deterioration.

There are various types of treatments that can be used in the preservation of flexible pavements including crack seal, fog seal, scrub seal, micro seal, slurry seal, thin overlay, cold milling, and rut filling. These preservation treatments are targeted at addressing pavement surface distresses primarily caused by the climate and environment and refer to Table 2-2 for the list of distresses. Using Indiana's historical data and expert opinion, Ong, Nantung, and Sinha developed a guideline for asphalt pavement preservation treatment selection as represented in Table 2-3. Crack seal, micro seal, and thin overlay are appropriate preservation treatments for use on both interstate and non-interstate roads, but chip seal is recommended only on interstate. None of the preservation treatments are recommended to treat the poor roughness condition. All preservation treatments are appropriate to treat up to medium severity cracking while micro seals and chip seals are not recommended to treat high severity cracking. All preservation treatments are recommended on the low severity rutting and only micro seal and thin overlay are recommended on the medium severity rutting. Micro seal, chip seal, and thin overlay are appropriate treatment on pavement with poor friction while crack seal is not.

With the addition of performance models, treatment rules, and treatment impact rules for each of the preservation treatments and each of the condition indices, the complexity of the modeling and data requirements increased tremendously. The increased data demands, and modeling requirements can be considered justifiable when the precision of the treatment cost estimates and condition predictions to differentiate distinct preservation treatment is beneficial. The agencies have the option to reduce the modeling effort by using treatment categories such as preventive maintenance, surface seal coats, and minor rehabilitation rather than the specific treatment in determining treatment needs. The agencies may choose to combine the two approaches both to yield the benefits associated with the use of modeling specific treatments for thin overlay and to reduce the modeling efforts by using treatment categories for preventive maintenance.

Table 2-3: Guidelines for Asphalt Pavement Preservation Treatment Selection (Ong, Nantung, & Sinha, 2010)

Pavement Conditions	Parameters	Asphalt Pavement Preservation Treatment			
		Crack Seal	Micro Seal	Chip Seal	Thin Overlay
Functional Class	Interstate	●	●	x	●
	Non-Interstate	●	●	●	●
Roughness (IRI)	Excellent	●	●	●	●
	Fair	●	●	●	●
	Poor	x	x	x	x
Crack Severity	Low	●	●	●	●
	Medium	●	●	●	●
	High	?	x	x	?
Rutting (Asphalt)	Low	●	●	●	●
	Medium	?	●	?	●
	High	x	?	x	x
Friction	Good	●	●	●	●
	Poor	x	●	●	●

Notes:
● Recommended
? May be recommended
X Not recommended

Agencies defining treatments or treatment categories or both, can establish trigger rules to define the conditions under which each of the treatments is recommended. Treatment trigger rules may be developed as decision trees or decision matrices, or both to help visualize the process and ensure that all possible combinations of circumstances are considered. While simple treatment rules typically consider pavement surface type, pavement condition rating, and traffic volumes or function classification, additional factors such as truck volumes, pavement structure thickness, and others can be considered to make treatment rules more complex. When the patterns in the historical data are not available or limited for use in setting the initial treatment rules, the experience and knowledge of experts in project and treatment selections are essential in establishing simple trigger rules and establishing trigger values which reflect the types of conditions under which pavement improvements are normally considered. Valuable information such as the number of years elapsed or the condition before a treatment is needed can be gathered from the experts. Once historical data become available, to help build credibility and calibrate treatment rules, treatment triggers may be revised every two to three years or even more frequently as necessary to reflect changes in treatment types or new policies. The accuracy of the treatment triggers can be evaluated and enhanced by conducting field visits and comparing field recommendations with the treatments recommended by running the analysis for the same section using the treatment rules.

However, the major challenges in implementing a pavement preservation program successfully to properly recommend treatment selection and timing are the lack of maintenance history needed in developing performance models and the inconsistencies in treatment definition and application. The development of models to assess the performance of pavement sections after preventive maintenance treatments requires a record of treatment applications or maintenance activities and collecting pavement condition indices that represent the benefits associated with the application of maintenance treatments and which can differentiate the performance characteristics of pavements that have received preventive maintenance treatments versus those that have not. Using a family modeling approach, preservation treatment performance can be modeled and used to recommend candidates for preservation treatment. By comparing these models to the control models (with no preventive maintenance), the benefit associated with preventive maintenance can be quantified.

Another challenge is the ability to track and measure the performance benefit using a meaningful performance indicator after preservation treatment. Crack sealing may result in a rougher pavement than if left untreated and if IRI is used as the performance measure, a negative benefit may result from the treatment. Most pavement management condition survey procedures were developed to identify and prioritize rehabilitation treatments. Therefore, agencies may be required to change their data collection procedures to capture pavement distresses such as sealed and unsealed cracking, fine cracking, raveling, weathering, flushing, and oxidation necessary to identify and trigger appropriate preventive maintenance treatments.

Numerous agencies have integrated pavement preservation programs into their PMS. Each agency tailored the elements in PMS to meet their pavement preservation program needs.

A comparison of three agencies is summarized in Table 2-4. In pavement preservation program, data collection may consider just a few distresses (i.e., cracking, rutting, and IRI that the Ministry of Transpiration of Ontario (MTO) collects) or as many distresses as Indiana Department of Transportation (INDOT) collects or as complex as Michigan Department of Transportation (MDOT). As part of the distress index MDOT collects alligator cracking, block cracking, longitudinal cracking, transverse cracking, patch or surface treatment, flushing, raveling, and shattered areas. The longitudinal cracking is then categorized into center lane, centerline, edge, and wheel path. All three agencies used regression analysis model to predict Ride Comfort Index (RCI) and Distress Manifestation Index (DMI) by MTO, Distress Index (DI) by MDOT, and Pavement Condition Rating (PCR), IRI, and Rut Depth by INDOT respectively. Preservation treatment decision trees or decision matrices may consider performance measures such as PCR, IRI, and Rut Depth only or may also consider other factors such as surface type, pavement age or remaining service life, and traffic level. Treatment reset value for a specific treatment may be represented by the PCI point increase, the year of life extension, or a Performance Jump (PJ) model and Deterioration Rate Reduction (DRR) model for each performance measure. Finally, in performing network level optimization analysis, MTO optimizes cost effectiveness of maintenance activity, MDOT maximizes benefit to cost ratio and INDOT optimizes the remaining service life extension (RSLE) of their entire pavement network.

Table 2-4: A Comparison of Components in Pavement Preservation Program

Evaluation Categories	Agencies with Pavement Preservation Program Integrated to PMS		
	Ministry of Transportation of Ontario (Bekheet, Helali, Kazmierowski, & Ningyuan, 2005)	Michigan Department of Transportation (Michigan Department of Transportation, 2020) and (Von Quintus & Perera, 2011)	Indiana Department of Transportation (Ong, Nantung, & Sinha, 2010) and (Lee & Shields, 2010)
Condition Index: Distress Types Collected	1. Ride Comfort Index (RCI): IRI 2. Distress Manifestation Index (DMI): cracking & rutting 3. Pavement Condition Index (PCI): RCI & DMI	1. Remaining Service Life (RSL) 2. Distress Index (DI): Alligator Cracking, Block Cracking, Longitudinal Cracking (i.e., Center Lane, Centerline, Edge, Wheel Path), Transverse Cracking (i.e., Straight or Irregular, Tears), Patch or Surface Treatment, Flushing, Raveling, Shattered Areas 3. International Roughness Index (IRI) 4. Rut Depth	1. Pavement Condition Rating (PCR): Fatigue Cracking, Reflective Cracking, Longitudinal Cracking, Transverse Cracking, Block Cracking, Edge Cracking, Pumping and Water Bleeding, Rutting, Flushing/Bleeding, Shoving, Potholes, Raveling, Patch/Patch Deterioration, Polishing, Lane/Shoulder Drop-off, or Heave 2. International Roughness Index (IRI) 3. Rut Depth
Performance Model	Non-linear regression model: RCI & DMI	Regression model: DI	Regression models: PCR, IRI, & Rut Depth
Parameter Triggering Treatment	1. Surface type 2. PCI 3. Pavement age 4. Traffic (AADT) 5. Raveling extent	1. RSL 2. DI 3. IRI 4. Rut Depth	1. PCR 2. IRI 3. Ruth Depth
Treatment: (Service Life Extension in Year or Improvement by PCI point)	1. Rout and seal: (2-3 years) 2. Mill and patch: (5-7 PCI points) 3. Micro seal: (10-12 PCI points) 4. Mechanized spray patch: (2-3 years) 5. Mill and pave: (Per performance model)	1. Non-structural HMA overlay: (5-10 years) 2. Surface milling with non-structural HMA overlay: (5-10 years) 3. Chip seal: (3-6 years) 4. Paver placed surface seal: (expected 4-8 years) 5. Micro seal: (3-5 years) 6. Crack treatment: (up to 3 years) 7. Overband crack filling: (up to 2 years) 8. HMA shoulder ribbons: (up to 3 years) 9. Ultra-thin overlay: (expected 4-8 years) 10. Fibermat: (3-6 years) 11. Cape seal: (5-7 years) 12. HMA overlay over chip seal/Texas underseal: (expected 5-10 years)	1. Crack Seal * 2. Micro Seal* 3. Chip Seal 4. Thin Overlay* 5. Patching* *Apply Performance Jump (PJ) and/or Deterioration Rate Reduction (DRR) effectiveness models (i.e., for Thin Overlay: $PJ_{IRI} = \exp\left(-1.5748 \times 10^{-8} IRI_b^2 - 0.01097 IRI_b + 4.7087\right)$ Fully restores PCR to 100 Fully restores rut depth to zero)
Optimization Method	Optimize cost-effectiveness	Highest benefit-cost ratio	Optimum remaining service life extension (RSLE) of the entire pavement network

2.3 PAVEMENT SURFACE TEXTURE

2.3.1 Overview of Pavement Surface Texture

Although the pavement surface characteristic, surface texture, is only a small part of the total pavement structure, its impact on the ride quality, safety, and noise are indisputable (AASHTO, 2012). The surface characteristics are of varying importance to different agencies. For example, residents and roadway users in rural areas are less concerned with the tire-pavement noise than those living by the urban freeways. Furthermore, the surface texture characteristics of pavement affecting the functional performance does not necessarily affect the structural performance, which is more critical to the agencies. Lastly, pavements with surface texture issues can be corrected by comparatively inexpensive treatments such as thin resurfacing or pavement preservation treatments.

Surface texture is defined as the deviation of the pavement from a true planar surface. Pavement surface roughness quality can be grouped into four different categories based on their wavelengths and peak-to-peak amplitude: microtexture, macrotexture, megatexture, and roughness or unevenness. Figure 2-1 illustrates these four different types of surface texture graphically. Microtexture is pavement surface texture with wavelength ranging from 1 μm (0.0004 in) to 0.5 mm (0.02 in) while macrotexture wavelength ranges from 0.5 mm (0.02 in) to 50 mm (2 in) and megatexture wavelength ranges from 50 mm (2 in) to 500 mm (20 in) (Henry J. J., 2000). Pavement roughness or unevenness is characterized by wavelengths longer than 500 mm (20 in). Numerous research studies have been conducted on pavement surface texture in general and the effect of different ranges of texture wavelength on pavement and tire interactions.

Pavement surface microtexture is characterized by individual fine and coarse aggregate material properties such as the degree of the polishing. Typically, limestone aggregates are very durable but often polished and thus have poor microtexture (Henry & Dahir, 1979). Ideally, aggregates with good microtexture provide resistance to polishing and wear at a rate just sufficient to renew its microtexture. Although increasing microtexture increases tire wear, sufficient microtexture is required to provide a good skid resistance pavement surface.

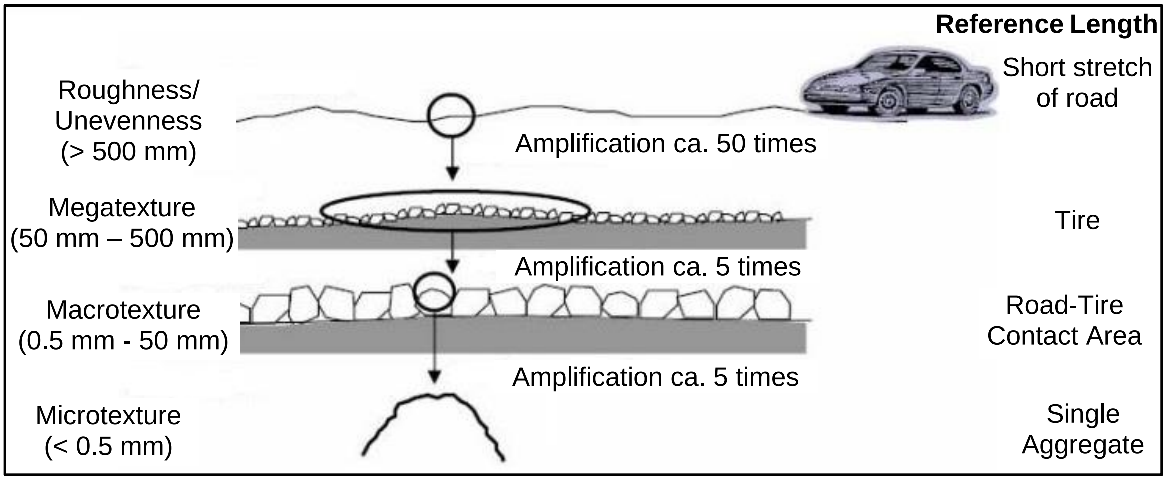


Figure 2-1: Four Types of Surface Texture (Hall, et al., 2006)

Macrotexture is characterized by the surface texture between individual aggregates and thus is influenced by mixture properties (shape, size, and gradation of aggregate) of the asphalt pavement surface wearing course or surface preservation treatment. Macrotexture is associated with the coarseness of pavement surfaces and is attributed to exciting shock absorbers in vehicle suspension systems, deforming tire sidewalls of a moving vehicle, affecting energy dissipation, wasting heat, and rolling resistance by vehicles (Praticò & Vaiana, 2015). Although macrotexture was shown to be the primary component of high-speed, wet skid resistance, study shows that increased macrotexture reduces accidents at lower speeds than previously believed (Henry J. J., 2000).

According to ISO 13473-5, Megatexture is characterized by the pavement surface smoothness resulting from depression or protrusion on the pavement. Megatexture with its wavelengths between macrotexture and roughness affects tire and pavement interaction and in-vehicle noise. Since the magnitude of megatexture is a result of pavement surface defects, distress, or “waviness” on the pavement surface including potholes or “washboarding”, megatexture on flexible pavement is undesirable.

Roughness or unevenness is characterized by undulations in the pavement surface and can be observed along the longitudinal or transverse direction of the pavement surface. Undulation along the flow of the traffic or the longitudinal unevenness caused by factors such as cracking or under designed, thin pavement layer on poor subgrade, affects the ride quality through vehicle vibrations. On the other hand, undulation in transverse direction, perpendicular to the flow of direction, caused by factors such as ruts or improper cross slope or warping affects safety in wet conditions through possible hydroplaning and vehicle rollover. Although pavement roughness is often included in the decision-making process for resurfacing treatment, fatalities and injuries resulting in litigation rarely are attributed to pavement roughness (Henry J. J., 2000).

The overall ride quality or pavement condition is primarily dictated by the roughness or smoothness of the ride the roadway users feel as they traverse the road section. As for public agencies with limited budgets, roadway construction and maintenance cost, pavement structural capacity, and durability play a major role in their selection of surface type. Considering all the factors that are important to both public agencies and roadway users, balancing the surface characteristics for comfort (smooth and quiet), durability, and economy without compromising the superior safety of the travelers are required (Ahammed & Tighe, 2010).

At the present time, the regular monitoring of surface characteristics as part of pavement management is primarily restricted to the longitudinal profile (Flinch and McGhee 2009). However, with the increasing emphasis on safety concerns, there is a growing interest in monitoring surface texture either directly or indirectly (by measuring friction or skid) and incorporating surface texture information into a pavement management analysis. Because of the repeatability of these measures, they are also becoming increasingly important as criteria for developing performance metrics for use with warranties and other performance-based contracts. Few agencies monitor noise at a network level, but this practice could also become more common in the future.

2.3.2 Pavement Surface Texture Assessment Methods

Over time asphalt pavement ages and oxidizes. Under traffic aggregate polishes and fine aggregate losses affect the pavement surface texture. Therefore, it is critical to periodically survey pavement surface texture in the field at the flow of the traffic using a reliable and practical pavement surface texture assessment method. Several standard pavement surface texture measuring methods are available that can be broadly categorized into two groups: (1) Direct measuring techniques such as the profilometer method and (2) indirect methods such as the volumetric and the British pendulum test.

Currently there is no reliable and practical method of measuring the properties of pavement microtexture in the field at the flow of traffic. Microtexture levels are commonly estimated indirectly using low speed friction measurement devices such as the British Portable Tester (BPT) and the Dynamic Friction Tester (DF Tester) in the field and in the laboratory and the locked wheel skid trailer when testing is performed at low speeds in the field. Since both microtexture and macrotexture are pavement surface textures, Li, Noureldin, and Zhu adopted the procedures for calculating the MPD of a macrotexture profile to analyze the microtexture data.

Microtexture can be measured in the field and in the laboratory using the British pendulum tester in accordance with ASTM standard test method ASTM E303-93, 2018. The British pendulum test method involves lowering of a pendulum type rubber slider to gently rest on a test surface that is cleaned and thoroughly wetted. The drag pointer and rubber slider are then lifted to the lock position by rotating them anti-clockwise. The testing began by pressing the release button and allowing the slider to swing over the test surface clockwise but catching the pendulum arm before swinging back and stopping the rubber slider from hitting the surface again. The value the drag pointer stops on the scale plate is recorded as the British pendulum number (BPN). The test is repeated three times and the average value represents the BPN for the surface microtexture.   A larger number indicates a higher surface friction: a higher surface friction between the slider and the test surface due to the microtexture of the surface produces a greater energy loss generating a larger BPN reading.

Another ASTM standard test method to measure microtexture in the field and in the laboratory is the Dynamic Friction (DF) tester (ASTM E1911-19, 2019). Unlike the British pendulum tester, which is based on energy loss since the DF tester method is based on the surface frictional properties as a function of sliding speed, the test is performed at various speeds to establish a friction and speed relationship. Preparation for the DF testing involves cleaning at least 500 by 500 mm (20 by 20 in) of flat laboratory test panels and in the field flushing with clean water the test surface. The DF tester unit consisting of flywheel, disk, motor, and three rubber sliders loaded to 11 N (2.65 lbf) by the leaf springs) is placed on the test surface. The test begins by rotating the disk until it reaches the target speed and ensuring the rubber sliders do not touch the test surface. The water tank supplies water flow of 3.6 L/min (0.95 gal/min) to maintain the wet condition of the test surface. Once the target speed is reached, the flywheel is lowered to allow the rubber slider to touch the surface. The friction measurements at 80 km/h (50 mph) (optional), 60 km/h (37 mph), 40 km/h (25 mph), and 20 km/h (13 mph) are recorded. The testing is completed when the flywheel and the water flow stops due to the friction between rubber and test surface. The test is repeated three times at various locations on the test surface and the average is recorded as the DFT numbers at and optionally.

ASTM E274/E274M standard test method specifies method to measure skid resistance of paved surfaces on a highway using a full-scale automotive tires which met the specification for standard rib tire (ASTM E501-08, 2015) or specification for standard smooth tire (ASTM E524-08, 2015). The testing equipment consisted of a vehicle with one or more test tires, trailer, transducer, instrumentation, water tank with dispensing system, and actuation controls for bake of the test tire. The test began with the vehicle accelerating to reach the standard test speed of 65 km/h (40 mph) and dispensing water at 600 mL/min·mm (4.0 gal/min·in) +/- 10 % to the pavement ahead of the test tire for 0.5 s. Then the brake is applied to the test tire and locks the wheel completely. The wheel-lock up point is marked, and tire-road interface force measurement is taken at not less than 0.2 s from the lock-up point and then additional measurements are recorded for an interval between 1.0 s and 3.0 s to generate a mean value to calculate skid number (SN). The testing is completed after the brake is released and the water supply is shut off. The skid resistance of the pavement surface represented by SN is calculated by dividing the force applied to slide the locked test tire at a target speed by effective wheel load and then multiplying by 100. For a project level pavement skid resistance evaluation, earlier researchers recommended using both tires as they provide a lot more information than using either tire by itself. However, at a network level evaluation, Henry and Wambold recommended using the smooth tire as it responded to both microtexture and macrotexture whereas a ribbed tire is more sensitive to microtexture.

The classic measure of pavement macrotexture is a volumetric method as specified in ASTM E965-15. This test can be performed in the laboratory and in the field. It involves cleaning the test surface with compressed air, brush, or both, spreading a known volume of dry material such as Ottawa natural silica sand or solid glass spheres on a clean and dry pavement surface with the disk tool in a circular motion, and measuring the diameter of the circular area covered by the material. The use of a portable windscreen around the test area to prevent wind, vibration, and moving traffic from affecting the test measurement is recommended. A minimum of four measurements of the diameter of a roughly circular patch of material is taken and the average of four equally spaced diameters is recorded. The macrotexture depth (MTD) of the test pavement surface is calculated using the following equation:

$$MTD\ (in\ mm) = \frac{Vol\ of\ Material(in\ mm^3)}{\pi * Average\ Diameter\ of\ area\ covered\ by\ the\ material\ (in\ mm)^2}. \qquad \text{Equation 2-1}$$

The Circular Track Meter is another standard test method for measuring pavement macrotexture properties that can be performed in the laboratory or in the field. In accordance with ASTM E2157-15, pavement macrotexture profiles can be obtained using a charge coupled device (CCD) laser-displacement sensor mounted on an arm at a diameter of 284 mm that rotates at a clockwise circular motion from a fixed elevation above the test surface. The CTM unit is placed on at least a 600 by 600 mm clean flat laboratory test panel or a dry, clean, and homogeneous pavement surface area without cracks or joints in the field. The CCD sensor measures vertical macrotexture depth at eight locations on a circular track at a spacing of 11.5 mm arc segment. CT Meter reports the mean profile depth (MPD) and the root mean square (RMS) values of the macrotexture profiles for the eight segments and the average of all segments. The average MPD from CT Meter is highly correlated with MTD from volumetric method that the following relationship expressed in millimeter was established:

$$MTD = 0.947\ MPD + 0.069. \qquad \text{Equation 2-2}$$

Flintsch, de León, McGhee, and Al-Qadi conducted research investigating the correlations between different measuring devices for pavement surface macrotexture on different hot mix asphalt (HMA) wearing surfaces and found excellent correlation between the CT Meter and the volumetric methods.

Road roughness or a longitudinal profile of a traveled surface can be measured using the static level method as specified in ASTM E1364-95. The surface elevations were measured at a constant interval of less than 305 mm (1 ft) for Class 1 resolution and 610 mm (2 ft) for Class 2 resolution along the two wheel tracks and recorded. The elevation can be obtained using conventional survey equipment or automated techniques such as laser-based systems. This test method is labor intensive since a team of three people can measure a profile at 305 mm (1 ft) interval for 0.64 km (0.4 mi) in a work day, with a resolution of 0.1 mm (0.0039 in). Therefore, the static level method is not suitable for a network level pavement roughness assessment.

As part of their collaborative research study, D'Angelo, et al. reviewed most relevant automated systems for monitoring asphalt pavement surface regularity and texture available in England for quality control/quality assurance (QC/QA) purposes in England. The study focused on assessing and comparing two laser scanning systems: 3D-TD, developed by MATtest Southern Ltd and MATtest Laser Straight Edge (LSE) with conventional methods. Based on their trial surveys performed on motorways in England, the 3D-TD system had a strong correlation with the Volumetric Patch results (94%) and presented a good repeatability. The LSE system correlated with the Rolling Straight Edge (RSE) results (80%) and presented a fair repeatability.

D'Angelo, et al also documented several vehicle-mounted surface texture measuring systems which use a laser line scanning and camera to render the 3D pavement surface. Pavement survey equipment such as ARAN, ARRB Hawkeye, Dynatest, ROMDAS, ERI, Pavision, PaveVision3D Ultra, SSI, and MATtest 3D-TD are equipped with the laser profile system. These units are expensive, costing upwards of $1M but are reliable and accurate and can detect other distresses such as cracks and rutting. The use of both the Laser Crack Measurement System (LCMS) and accelerometer makes Dynatest, ARRB, ROMDAS and ARAN a more accurate system in calculating the pavement surface irregularities.

In their research, Sahhaf and Rahimi described LCMS and presented the potential and applicability of the road surveying system. LCMS has an adjustable sampling rate between 5,600 to 11,200 profiles per second and its operational speed ranges from 0 to 100 km/h (62 mph). LCMS allows the automatic detection of cracks and the evaluation of rutting, macrotexture and other road surface features such as IRI, slope, potholes, raveling, sealed cracks, joints in concrete, tinning, and others. Because LCMS scans the entire 4 m width of the pavement surface with 1 mm resolution at highway speeds, it can evaluate texture continuously over the entire pavement surface instead of measuring at a single point. Deriving from the Sand Patch volumetric approach, LCMS's texture output, Road Porosity Index (RPI) is the volume of voids in the road surface occupied by the and over the surface area and is calculated using the following equation:

$$Road\ Porosity\ Index\ (RPI) = \frac{(Vol_{air\ void} - Vol_{raveling} - Vol_{cracks})}{(Surface\ Area)}\ . \qquad \text{Equation 2-3}$$

In order to validate texture value from LCM, RPI measurements are compared to the Mean Profile Depth measurements collected by standard 64kHZ texture laser on various test sections. Since a high degree of correlation (88%) between RPI-LCM method and MPD measurements were observed, the authors concluded that laser devices outputs are accurate and repeatable.

Megatexture is measured using a similar profiling method as measuring pavement roughness. The standard test method for measuring pavement roughness using a profilograph is specified in ASTM E1274-18. The pavement roughness is measured with a profilograph traveling at a speed less than 15 km/h (3 mph) therefore requires proper traffic control devices to operate in traffic. Before beginning the test, the test section is cleared of debris and the profilograph is moved forward about 10 m (30 ft) beyond the start point and the first measurement is recorded. The successive profilograph measurements taken at every 30 m (100 ft) interval and the longitudinal distance from the start position are recorded.

ASTM E950 / E950M-09 specifies the standard test method for measuring the longitudinal profile of the test section with a vehicle equipped with transducers and profile computing and recording equipment. At the beginning of each collection day, the equipment operator needs to be familiar with the test section location and turn on electronic equipment and allow it to stabilize and perform daily calibration checks. Profile data quality is better at a higher speed. Measuring speed higher than 25 km/h (15 mph) is recommended and measurements below 2 m/s (5 mph) is not practical.

2.3.3 Integration of Pavement Surface Texture to PMS

Pavement wearing surfaces are designed and constructed to provide good friction, low levels of roughness, and low level of noise (Ahammed & Tighe, 2010) and (Flintsch, de León, McGhee, & Al-Qadi, 2003). Since the 1990s, Federal Highway Administration (FHWA) has been requiring each state to report IRI data for the interstate system, other principal arterials, and rural minor arterials. Although pavement surface microtexture, macrotexture, and megatexture assessments are not typically performed as part of a network-level survey for PMS analysis, many agencies have been collecting and reporting roughness measures, IRI for PMS analysis. IRI value is based on an objective pavement roughness measurement and delivers consistent data for trend analyses and across jurisdictions. FHWA recommends IRI data for all other functional systems such as rural major collectors, urban minor arterials, and urban collectors. For highways, FHWA classifies an IRI rating of less than 1.50 m/km (95 in/mi) as good ride quality and IRI of less than 2.70 m/km (170 in/mi) as acceptable. However, currently there is no IRI standard established for local, collector, or arterial roadways in urban environments. The application of pavement surface roughness to PMS is presented using two case studies performed in Urban network: Denver in Colorado and Washington in District of Columbia.

The city and county of Denver (CCD) in collaboration with University of Colorado Denver investigated the use of roughness measure, IRI, as a measure of performance for all future repaving projects for the urban road network. Their work involved establishing expected IRI so as to allow CCD to assess the quality and roughness of roadways and establish a viable pavement evaluation tool for the CCD to assist in resource allocation and construction planning practices in Denver (Rens & Staley, 2010). IRI data was collected using a laser inertial surface analyzer (LISA Model 6200) developed by Ames Engineering. The dual laser system was mounted to a John Deere brand Gator utility vehicle and traveled at approximately 16 km/h (10 mph) along the segments being analyzed. Roadways were analyzed using the pavement profiler at least two times in each direction of travel and for the repeatability study, roadways were analyzed multiple times using multiple drivers.

Rens and Staley performed the IRI study on 23 locations for a total of 31.19 km (19.38 mi) in the CCD along an urban roadway planned for repaving. Roadway segments ranged from 0.47 km (0.29 mi) to 2.37 km (1.47 mi) in length. IRI data for both before and after construction repaving was collected to assist in establishing urban roadway roughness threshold on the newly repaved surfaces. IRI values for the before repaving conditions ranged from about 3.50 m/km (222 in/mi) to about 6.63 m/km (420 in/mi). Based on FHWA metrics, none of the 23 locations met the IRI threshold level of 2.37 m/km (150 in/mi) for an acceptable ride prior to repaving. After repaving, IRI values ranged from about 1.53 m/km (97 in/mi) to about 5.95 m/km (377 in/mi) which means all 23 locations did not meet metrics for good criteria. 51% of the repaired segment by length met the metric for an acceptable ride while 49% of segment by length did not meet the acceptable ride criteria. However, after repaving, a weighted average of IRI values for 23 test locations improved by approximately 36%. For a section with the greatest IRI improvement, IRI before overlay was 3.99 m/km (252.99 in/mi) and after overlay was1.57 m/km (99.51 in/mi) respectively. Moreover, all 23 locations exhibited a ride that was normal, or by historical CCD standards met expectations, for a newly overlaid pavement surface. Therefore, their study suggested a more reasonable IRI range suitable for the urban environment. IRI values less than 2.37 m/km (150 in/mi) are good while values less than 3.47 m/km (220 in/mi) are acceptable.

Rens and Staley also presented factors influencing IRI values which are unique to urban environments: including shorter road segments, variable travel speed due to traffic control devices and congestion. In addition, their study shows manhole covers on the road and street crossings affect IRI value. In order to limit the factors influencing the IRI value, raters noted their locations and removed IRI data collected over them when calculating IRI for the pavement section.

Arhin, Noel, and Ribbiso developed a model to predict IRI based on Present Serviceability Rating (PSR) for the District of Columbia (DC). PSR is the subjective ride quality perceived and rated by the motorists. Urban areas such as the DC street network consisted mostly of arterials, collectors and local streets. Their study was based on surveying 66 local motorists who formed three (3) groups of 23 participants. Each group was assigned to drive over a preselected lane and based on their perception of ride smoothness had the option to rate a range of 0 (impassable) to 5 (perfect). They presented IRI thresholds based on the model developed for various street classifications. The good quality ride IRI threshold for freeway is less than 1.96 m/km (124 in/mi), less than 2.87 m/km (182 in/mi) for arterials and less than 2.97 m/km (188 in/mi) for collectors. The acceptable quality ride IRI threshold for freeway is between 1.96 m/km (124 in/mi) and 3.44 m/km (218 in/mi), between 2.87 m/km(182 in/mi) and 4.43 m/km (281 in/mi) for arterials and between 2.97 m/km (188 in/mi) and 5.02 m/km (318 in/mi) for collectors. Generally in the urban area, travel speed is lower due to traffic congestion and traffic interruptions. At a lower speed, motorists perceive and rate the ride quality more favorably and have a greater tolerance for pavement roughness. DC’s acceptable IRI thresholds were developed based on the high correlation at 95% confidence interval between the perception of ride quality and IRI values.

The pavement surface macrotexture depends primarily on factors such as maximum aggregate size, aggregate gradation, and aggregate shape and is also influenced by asphalt content and air voids (Stroup-Gardiner & Brown, 2000). Therefore, macrotexture varies as mix properties change but the change in macrotexture causing pavement segregation is comparative regardless of mix properties. The change in macrotexture is the ratio of macrotexture for a given level of segregation to the non-segregated areas. The change in macrotexture ratio for low, medium, and high levels of segregation are 1.36, 1.76, and 2.59, respectively (Stroup-Gardiner & Brown, 2000). Automated survey methods can be used to evaluate pavement surface macrotexture and can be performed quite efficiently so that it may be utilized in hot mix asphalt construction for quality assurance or control purposes. In the study performed by Flintsch, de León, McGhee, and Al-Qadi, macrotexture applications are limited to measuring frictional properties of the pavement surface and detecting hot mix asphalt construction segregation or non-uniformity. Based on their study, Flintsch, de León, McGhee, and Al-Qadi also proposed a model to predict macrotexture using wearing surface mix properties. Tsai and Wang on the other hand developed a set of algorithms to automatically detect and classify asphalt pavement raveling using the 3D pavement surface textures captured by the 3D laser technology. The research work done in developing algorithms to detect and classify raveling is in its early stage and the outcomes are often still not acceptable and transportation agencies have difficulty in implementing the algorithms (Tsai & Wang, 2015).

2.4 KNOWLEDGE GAPS

This chapter presented a literature review exploring the pavement management system and pavement surface roughness. Based on the literature review conducted, there were two main concepts tailored to the needs of the pavement preservation program that were missing. First, based on the literature review, the pavement condition to perform the network level PMS for the preservation program is no different from the PMS for the maintenance, rehabilitation, and reconstruction. Since pavements that are in a structurally sound condition are good candidates for preservation treatment, a simple, possibly a single, performance measure to represent the overall condition of the pavement may be viable. This will allow agencies to be more flexible with their preservation treatments and minimize the pavement performance modeling effort. Secondly, the pavement surface texture roughness indicator to measure the performance of pavement surface texture deficiency is missing. Agencies had been using IRI to capture pavement roughness. However, pavement preservation treatment is not intended to correct the roadway profile which is captured by the IRI. Therefore, a performance indicator to capture pavement surface texture roughness is necessary for triggering preservation treatment.

CHAPTER 3

EVALUATION OF CITY OF PHOENIX PAVEMENT PRESERVATION PROGRAM

3.1 INTRODUCTION

A successful implementation of the pavement preservation program is dependent on several non-technical and technical factors. This chapter explores non-technical components such as stakeholder partnerships, institutional collaboration, and pavement management team workforce, and major technical components including road inventory data, pavement condition data analysis, and PMS analysis parameters. The objective of this portion of the research work is to evaluate the current City of Phoenix pavement preservation program. As shown in Figure 3-1, City of Phoenix PMS workflow began with the roadway inventory data and budget allocated to perform annual maintenance work. The pavement condition data is collected all year-round using ARAN 9000. Once a year, pavement condition analysis, optimization, prioritization, and budgeting analysis are performed to program a maintenance treatment plan for three years out in the future (i.e., a preservation treatment program for a project to begin in Summer of 2023 was developed in Spring of 2020). With an upgrade to ARAN 9000 with LCMS technology in December 2017, although not perfect, fatigue cracks are captured better than the previous collection system. Therefore, there is a need to re-evaluate and establish criteria for different types of distresses the new van collects. There is also a need to reevaluate pavement performance models that were established when PMS was first implemented in 2008 after at least three datasets are collected. Due to the data availability, this chapter will not cover an evaluation of the PMS feedback process.

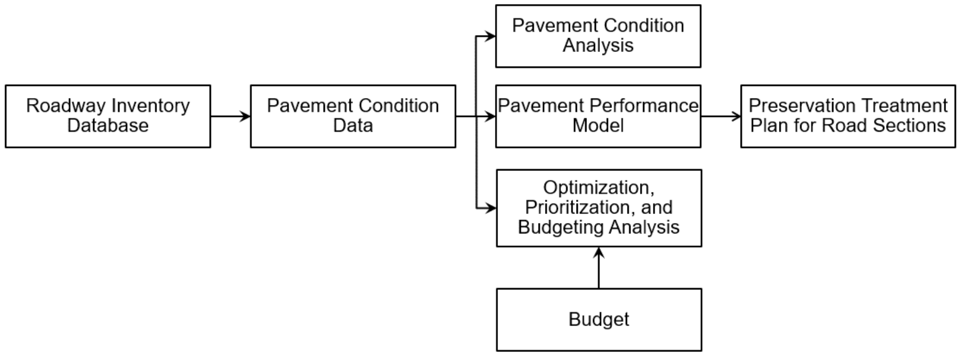


Figure 3-1: Overview of City of Phoenix Pavement Management System Workflow

3.2 NON-TECHNICAL FACTORS

3.2.1 Stakeholder Partnerships

The agreement to support the decision to implement the pavement management system from the upper management, elected officials, public, and stakeholders is required in developing the work plan that ensures PMS continues to reflect agency policies and practices and to guide the future funding needs. Communication is the key to the success of any partnership. When presenting information to the partners, it is critical to provide clear and relevant information with sufficient level of detail. The information is then to be delivered in a manner accessible to all stakeholders and provide them with opportunities to comment, respond, or ask questions for clarification or additional information.

In August 2015, Phoenix voters approved a 35-year transportation plan, known as Transportation 2050 (T2050). T2050 requires a 15-member Citizens Transportation Commission (CTC), the citizen-led, mayor, and councilmembers appointed committee of transportation experts and community stakeholders to improve citywide streets and transit services. CTC's responsibilities include addressing the street transportation needs and providing an oversight on the expenditure of funds. CTC takes on the leadership role in driving the change and management in sustaining the changes within the City of Phoenix. In 2019, the City of Phoenix Street Transportation Department requested CTC to recommend the Accelerate Pavement Maintenance Program (APMP) authorizing the advancing $200 million to accelerate pavement maintenance projects which were part of the original five-year work plan for 2019 through 2023 for City Council approval.

The unanimous support from the management and the overwhelming support from the public that the Street Transportation Department received is apparent with the initiation of APMP. The City of Phoenix Street Transportation Department holds public meetings, hosts interactive pavement maintenance dashboards, creative signage, and interacts with the public and customers using social media and news media to keep the stakeholders informed and updated. A total of 223 public inquiries or requests of locations to be considered in the APMP were received and evaluated by the pavement management personnel for consideration.

3.2.2 Institutional Collaboration

Since the City of Phoenix is a large, decentralized organization, even different departments or divisions working in the street right of way tend to operate in “silos”. Since pavement management information is cross-functional, the traditional organizational silos need to be broken and regular information sharing, and coordination of capital improvement plans and maintenance activities and collaboration among departments and divisions need to be encouraged instead. Pavement management requires an on-going commitment of resources to update the pavement condition information and to run the analysis. Providing these resources can be a challenge. Therefore, it is important for various departments or divisions in the city affecting pavements to understand the benefits of PMS and the importance of quality data.

The City of Phoenix Pavement Management team, responsible for managing the pavement preservation program, has been collaborating with the personnel who work in the street right of way. For several years, the Pavement Management team has been meeting with personnel from Traffic Services (responsible for stripping), Programming and Project Delivery Division (responsible for major roadway infrastructure improvements), Planning and Development Department (responsible reviewing and approving roadway infrastructure improvements by developers and contractors), Water Services (responsible for providing water to the community), and utility companies on a weekly, monthly, or quarterly meetings. These meetings are conducted to review conflicts and document maintenance, rehabilitation, or new roadway construction activities.

The major achievements from the collaborations are a revision to the City's long-standing pavement cut policy and a reliable and current maintenance history data in PMS. Each year right-of-way stakeholders, primarily utility companies and private developers, made between 6,000 and 7,000 pavement cuts into the road network. Regardless of how well a pavement cut is performed, it leaves a negative and lasting impact to the surrounding pavement as well as the soil under it that it reduces the service life of that pavement. To encourage coordination of project work that will cut into the streets and to ensure the streets are adequately restored after being cut, the city adopted a two-year moratorium on street cuts to protect new pavement and required an asphalt mill and overlay for cuts into pavements less than two years old. The city also required slurry or micro seal treatments for pavement cuts regardless of pavement age.

3.2.3 Pavement Management Workforce

Agencies cannot always control or plan for all transitions in staffing or employees taking leaves. However, the agency can plan to make sure PMS remains operational even when changes are inevitable. Currently, the city has only one technician who can both collect data and process the data. A second technician can drive the van and collect data but cannot process the data. Therefore, there is a need for a support person so data collection and processing can be performed as scheduled without interruption.

Due to the staffing shortage, a review of pavement condition data has not been performed. There were 2252 sections (14%) of 15570 PM analysis inventory sections that were either omitted or processed unsuccessfully from the 2021 collection year. With the street network as large as the City of Phoenix, it is necessary to have a dedicated pavement engineering team to review the data collected and to maintain and update the pavement condition data as well as pavement maintenance and construction history. The city contracted an asset management company, Deighton Associates, to help perform PMS analysis. However, there is still a need to have a dedicated pavement engineering team to review the analysis model, parameters, and results.

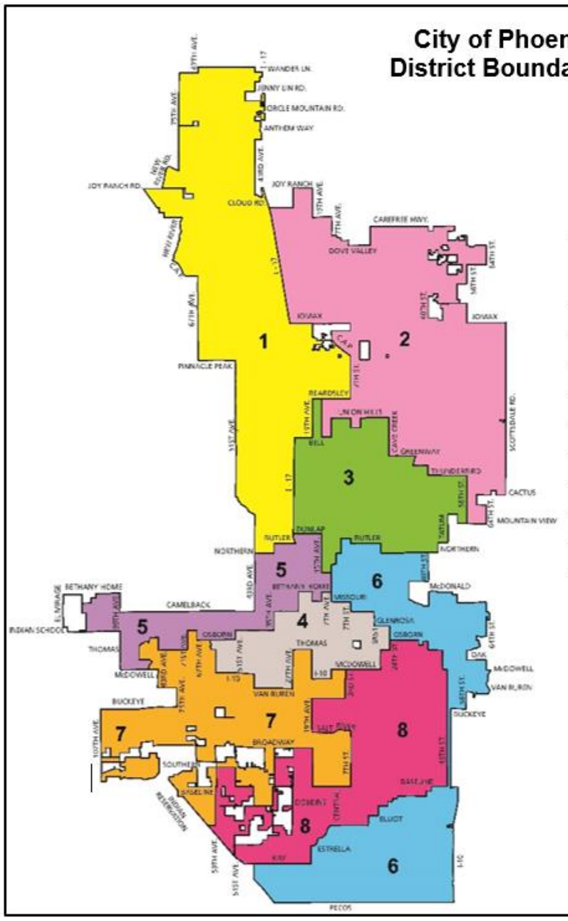
3.3 EVALUATION OF ROAD INVENTORY DATA

3.3.1 Overview of Road Inventory Data

Pavement inventory data identifies, classifies, and quantifies various aspects of the pavement network; updates reflecting changes in the network or changes in its characteristics are essential to an effective pavement management system. The inventory database that supports the City of Phoenix pavement management system includes the following: inventory section identification number, street name, the section beginning and end cross streets, super section or quarter section identification number, functional classification, segment length, average pavement width, pavement type, pavement thickness, traffic volume, council district, pavement history data, and pavement condition data and collection date. Typically, even within a single agency or municipality, roadway inventory data needed for pavement management is often maintained by different divisions and stored in different software and databases.

On June 20, 2019, the Pavement Management Engineering team held a meeting with City of Phoenix staff from Traffic Services, Design and Planning, Materials Lab, Geographic Information System (GIS), Private Development Review, and Floodplain Management sections. During the meeting, the locations where various data relevant to pavement management were stored, how often the data were updated, and how long the data were retained were discussed. All data except for new roadway construction or improvement to existing roads performed by the developer and the drainage problem were housed in the GIS database. Therefore, data integration can be performed using the GIS analysis tool. Unfortunately, data retention time being only ten years and absence of systematic traffic data and complaint driven drainage assessment posed a limitation on keeping pavement inventory data up to date. Based on a review of historical pavement condition data and verified by reviewing the right of way images captured by the van and Google Street View, it is apparent that soil condition and drainage condition in Phoenix influence the pavement performance. The pavements around the foothills or at the low spots lacking positive drainage are prone to flooding or ponding water. However, factors such as traffic, drainage, and soil condition which affect the pavement performance are currently not collected or used for PMS analysis.

The City of Phoenix is divided into eight council districts and the street network in each district by centerline kilometers (miles) as shown in Figure 3-2. The city’s goal is to evenly distribute maintenance effort to all eight council districts according to the proportion of centerline kilometers (miles) of roadway in each council district. Each year approximately 13.85 % of the annual pavement maintenance program budget is allocated to District 1, 16.16 % to District 2, 11.79% to District 3, 8.49% to District 4, 9.31% to District 5, 13.46% to District 6, 12.91% to District 7, and 14.03% to District 8.



2020 Centerline Kilometers (Miles) by Council District	
District 1:	1,085 km (674 mi); 13.85%
District 2:	1,267 km (787 mi); 16.16%
District 3:	924 km (574 mi); 11.79%
District 4:	665 km (413 mi); 8.49%
District 5:	729 km (453 mi); 9.31%
District 6:	1,054 km (655 mi); 13.46%
District 7:	1,011 km (628 mi); 12.91%
District 8:	1,099 km (683 mi); 14.03%
Total:	7,833 km (4,867 mi); 100%

Figure 3-2: City of Phoenix Council District Boundaries and Centerline Kilometers (Miles) by District

The City of Phoenix pavement maintenance section maintains flexible pavement only. Throughout the city, there are a few concrete pavement sections, but they are serviced on as needed by the inhouse field crew that concrete pavements are not a part of the programmatic pavement maintenance program. The streets are divided into five street classifications: arterial, collector, major arterial, and minor collector. The GIS service team maintains and updates street centerline kilometers by street classification annually. Table 3-1 shows the street centerline kilometers (miles) over the past ten years starting in 2011. New development constitutes most of the new local streets and streets acquired by developers such as for Grand Canyon University constitutes most of the abandoned streets. Arterial and major arterial are combined and classified as the arterial street in pavement management inventory data.

3.3.2 Evaluation of Maintenance History Data

Road inventory data is stored in Deighton Associates' PMS analysis software dTIMS. For the PMS analysis purpose, it is critical to update pavement maintenance history as it affects the analysis directly. PMS analysis takes into consideration years since construction or major maintenance activities to avoid treated streets which warrant a treatment based on pavement condition but is too soon to receive treatment based on the City of Phoenix pavement maintenance treatment cycle. Table 3-2 shows the number of kilometers (miles) treated each year by treatment type and street classification. Based on the historical data, the maintenance treatment cycle is about 60 years beginning with an overlay treatment, and subsequent fog seal, crack seal, and micro seal or surface before receiving another round of overlay treatment. Therefore, a street that received treatment does not get another treatment regardless of treatment type for another 15 years.

Although maintenance work done by the City of Phoenix pavement maintenance section has been updated annually, it was observed that the construction or maintenance activities performed by developers, utility companies, and other departments or divisions within the city were not. Since Esri geographic information system (GIS) is used as the mapping tool across departments in the City of Phoenix and to store information on construction activities and locations, shapefile of the routes driven by ARAN was exported and spatially joined, to generate attribute table with construction and maintenance history data for each PMS street section. Unfortunately, information on construction and maintenance performed by developers and agencies outside of the city are not accessible in the GIS map and it is not feasible to update the maintenance history data systematically.

3.3.3 Pavement Maintenance System Inventory Section

The City of Phoenix PMS consisted of 15,570 sections and 2,858 super sections or quarter sections. Since there is only one technician processing the data, pavement condition data collected were not reviewed after processing. However, steps are taken to verify all street networks in the City of Phoenix are surveyed. The processed data are reviewed graphically by overlaying an ARAN driven route shapefile into the City of Phoenix GIS base map. The processed data are also reviewed to ensure that distress data are not missing from the condition report for the sections that were collected. New streets that are constructed or streets that are abandoned are noted and updated in the PMS by adding new street sections or retiring the abandoned streets.

Generally, pavements in a similar condition and in the same family are grouped to form super sections or quarter sections for PMS analysis and to ensure they receive the same treatment. Previous practice of grouping adjacent arterial and major collector sections or pavements within the city-defined quarter mile grid to form quarter sections, resulted in grouping of pavements that are vastly different in condition. The super section or quarter section condition represented the average condition and did not truly represent the condition of any pavement section within the super section or quarter section. Also, local streets and minor collector streets within a quarter section may be divided by the natural barrier or man-made barrier such as freeway so that the maintenance of quarter section or super section may be performed at different times due to constructability issues. In the PMS analysis, once a super section or quarter section is committed for a treatment, the section within the quarter section or super section is left out from the maintenance, thus regrouping and redefining of the quarter sections was done.

Table 3-1: Street Centerline Kilometers (Miles) by Street Classification from 2011 to 2020

Street Classification	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Δ Over 10 Years (%)
Arterial	729 km (453 mi)	732 km (455 mi)	731 km (454 mi)	727 km (452 mi)	729 km (453 mi)	729 km (453 mi)	707 km (439 mi)	697 km (433 mi)	698 km (434 mi)	692 km (430 mi)	-5.18%
Collector	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	216 km (134 mi)	0.57%
Local	5,609 km (3,485 mi)	5,615 km (3,489 mi)	5,629 km (3,498 mi)	5,636 km (3,502 mi)	5,643 km (3,507 mi)	5,644 km (3,507 mi)	5,660 km (3,517 mi)	5,684 km (3,532 mi)	5,710 km (3,548 mi)	5,728 km (3,559 mi)	2.12%
Major Arterial	438 km (272 mi)	441 km (274 mi)	439 km (273 mi)	455 km (283 mi)	456 km (283 mi)	460 km (286 mi)	451 km (280 mi)	451 km (280 mi)	438 km (272 mi)	436 km (271 mi)	-0.06%
Minor Collector	764 km (475 mi)	764 km (475 mi)	768 km (477 mi)	769 km (478 mi)	770 km (478 mi)	769 km (478 mi)	768 km (477 mi)	763 km (474 mi)	764 km (475 mi)	761 km (473 mi)	-0.43%
Total Street Centerline km (mi)	7,755 km (4,819 mi)	7,768 km (4,827 mi)	7,783 km (4,836 mi)	7,804 km (4,849 mi)	7,814 km (4,855 mi)	7,818 km (4,858 mi)	7,800 km (4,847 mi)	7,810 km (4,853 mi)	7,826 km (4,863 mi)	7,833 km (4,867 mi)	1.01%

Table 3-2: Pavement Maintenance Program Kilometers (Miles) by Treatment Between Fiscal Year 2012 and 2021

Treatment Program	FY'12	FY'13	FY'14	'FY15	FY'16	FY'17	FY'18	FY'19	FY'20	FY'21
Arterial & Major Crack Seal		4.7 km (2.9 mi)				45.5 km (28.3 mi)	20.1 km (12.5 mi)			
Arterial & Major FAST			2.4 km (1.5 mi)			0.8 km (0.5 mi)	1.1 km (0.7 mi)			
Arterial & Major Fog Seal					27.2 km (16.9 mi)	32.3 km (20.1 mi)	41.7 km (25.9 mi)	57.3 km (35.6 mi)	48.1 km (29.9 mi)	66.9 km (41.6 mi)
Arterial & Major Micro Seal	0.8 km (0.5 mi)				14.8 km (9.2 mi)	19.5 km (12.1 mi)	19.0 km (11.8 mi)	20.9 km (13.0 mi)	9.5 km (5.9 mi)	7.4 km (4.6 mi)
Arterial & Major Thin Overlay					15.1 km (9.4 mi)	27.0 km (16.8 mi)	22.7 km (14.1 mi)	81.1 km (50.4 mi)	83.5 km (51.9 mi)	69.2 km (43.0 mi)
Arterial & Major Seal Coat						0.5 km (0.3 mi)				
Local & Minor Crack Seal		50.1 km (31.1 mi)				93.3 km (58.0 mi)	61.8 km (38.4 mi)			
Local & Minor FAST	0.8 km (0.5 mi)	38 km (23.6 mi)	31.2 km (19.4 mi)	27.2 km (16.9 mi)	13.7 km (8.5 mi)	20.3 km (12.6 mi)	21.2 km (13.2 mi)	34.1 km (21.2 mi)	33.6 km (20.9 mi)	32.0 km (19.9 mi)
Local & Minor Fog Seal								56.2 km (34.9 mi)	75 km (46.6 mi)	67.1 km (41.7 mi)
Local & Minor Micro Seal		3.4 km (2.1 mi)								
Local & Minor Thin Overlay	136.5 km (84.8 mi)	43.6 km (27.1 mi)	82.1 km (51.0 mi)	117 km (72.7 mi)	78.1 km (48.5 mi)	168.2 km (104.5 mi)	97.2 km (60.4 mi)	211.3 km (131.3 mi)	342.0 km (212.5 mi)	18.2 km (11.3 mi)
Local & Minor Seal Coat						169.1 km (105.1 mi)	39.3 km (24.4 mi)	32.5 km (20.2 mi)	36.2 km (22.5 mi)	38.1 km (23.7 mi)
Local & Minor Slurry Seal	54.9 km (34.1 mi)	48.9 km (30.4 mi)	54.4 km (33.8 mi)	57 km (35.4 mi)	54.9 km (34.1 mi)	171.7 km (106.7 mi)	119.1 km (74.0 mi)	110.9 km (68.9 mi)	116.8 km (72.6 mi)	109.6 km (68.1 mi)
Major Collector Crack Seal		0.8 km (0.5 mi)			40.7 km (25.3 mi)		3.9 km (2.4 mi)			
Major Collector FAST						0.5 km (0.3 mi)				
Major Collector Fog Seal					4.5 km (2.8 mi)	2.1 km (1.3 mi)	6.4 km (4.0 mi)	8.0 km (5.0 mi)	6.0 km (3.7 mi)	11.1 km (6.9 mi)
Major Collector Micro Seal		1.8 km (1.1 mi)		1.1 km (0.7 mi)	5.8 km (3.6 mi)	1.6 km (1.0 mi)	3.2 km (2.0 mi)	5.0 km (3.1 mi)	0.8 km (0.5 mi)	2.3 km (1.4 mi)
Major Collector Thin Overlay	15.9 km (9.9 mi)	14.8 km (9.2 mi)	29.8 km (18.5 mi)	7.7 km (4.8 mi)	52.0 km (32.3 mi)	0.8 km (0.5 mi)	2.7 km (1.7 mi)	7.1 km (4.4 mi)	8.7 km (5.4 mi)	9.3 km (5.8 mi)
Total Kilometers (Miles) Treatment	208.9 km (129.8 mi)	205.7 km (127.8 mi)	199.9 km (124.2 mi)	210.0 km (130.5 mi)	306.4 km (190.4 mi)	753.5 km (468.2 mi)	459.5 km (285.5 mi)	624.3 km (387.9 mi)	760.3 km (472.4 mi)	431.1 km (267.9 mi)
Percent of Network Treated	2.69%	2.65%	2.57%	2.69%	3.92%	9.64%	5.89%	7.99%	9.71%	5.50%

3.4 PAVEMENT CONDITION DATA ANALYSIS

3.4.1 Pavement Condition Data Collection System

Prior to 2018, pavement condition survey was performed using the ARAN III model and had issues detecting and classifying fatigue cracks. The new ARAN 9000 equipped with LCMS, as illustrated in Figure 3-3, can detect far more distresses automatically and at a greater accuracy than its predecessor although far from being a perfect system. Since 2008, pavement condition data collected and classified were fatigue crack, longitudinal wheel path crack, longitudinal non-wheel path crack, transverse crack, and IRI. The severity ranging from low, medium, to high and the extent ranging between 0 to 100 % of each distress are classified and rated by Vision software but deduct values and distress index are calculated in dTIMS.

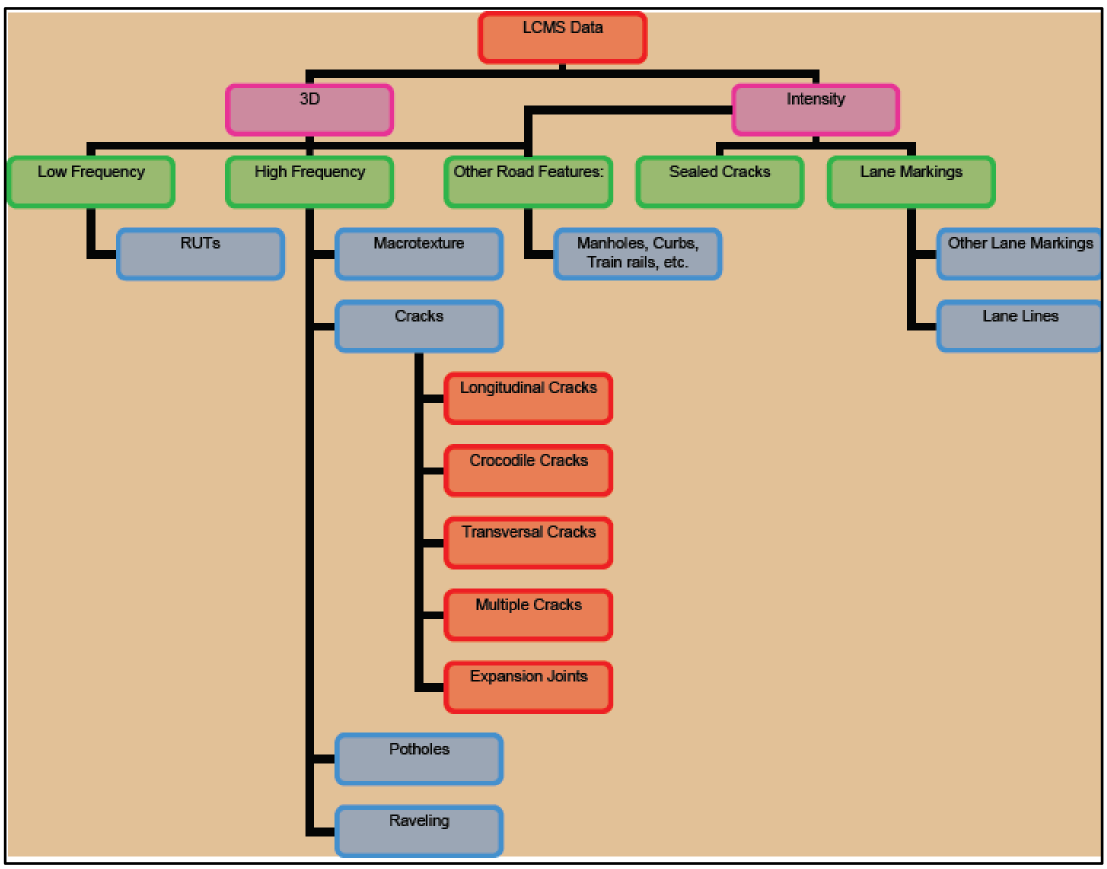
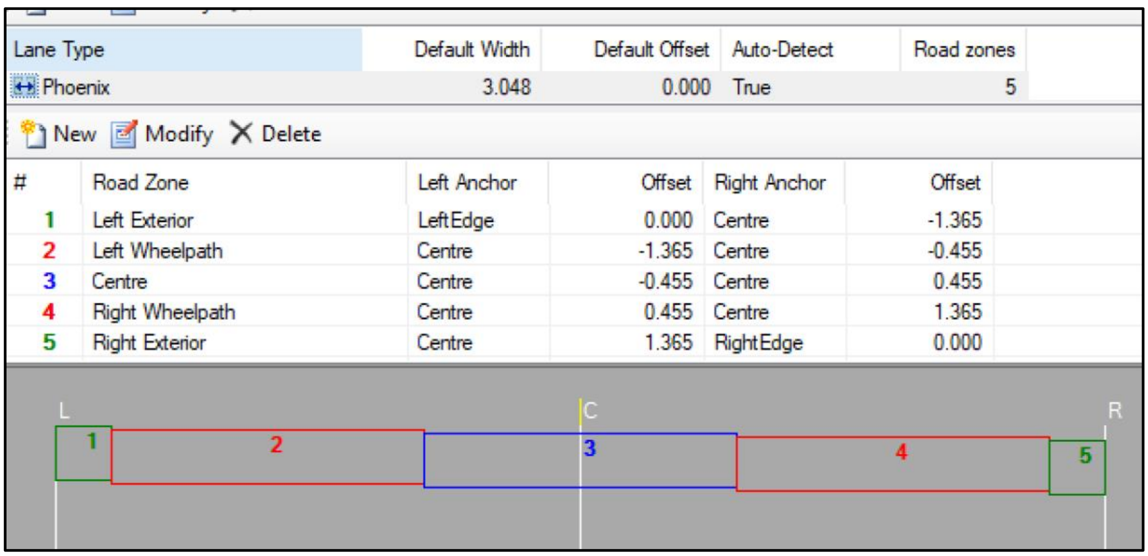


Figure 3-3: Types of Distresses Assessed by LCMS

3.4.2 Pavement Condition Rating Methodology

Based on the pavement distresses prevalent in the City of Phoenix network and LCMS capability, pavement distresses including fatigue cracks in the wheel path, fatigue cracks in non-wheel path, longitudinal cracks in wheel path, longitudinal cracks in non-wheel path, transverse cracks, macrotexture in wheel path, and IRI in wheel path are collected. Although the ARAN van can scan up to 4 m (13 ft) of pavement in the direction of travel, for the purpose of analyzing distresses within a single lane, distresses within the 3 m (10 ft) width on the driven lane are rated. The 3 m (10 ft) pavement condition assessment cross section is divided into five zones. Figure 3-4 illustrates five road zones: left exterior, left wheel path, center, right wheel path, and right exterior. The wheel paths and the center between the wheel paths are 0.9 m (3 ft) and the space outside of the wheel paths to the left or the right edge of the pavement detection zone are 0.15 m (6 in).



Lane Type	Default Width	Default Offset	Auto-Detect	Road zones
Phoenix	3.048	0.000	True	5

#	Road Zone	Left Anchor	Offset	Right Anchor	Offset
1	Left Exterior	LeftEdge	0.000	Centre	-1.365
2	Left Wheelpath	Centre	-1.365	Centre	-0.455
3	Centre	Centre	-0.455	Centre	0.455
4	Right Wheelpath	Centre	0.455	Centre	1.365
5	Right Exterior	Centre	1.365	RightEdge	0.000

Figure 3-4: Pavement Condition Assessment Road Zones

In general, pavement distresses for the maintenance treatment purpose can be categorized into surface cracking, surface texture, and surface deformation. Cracking is to be captured by fatigue crack, longitudinal wheel path crack, longitudinal non-wheel path crack, and transverse crack. Bleeding and raveling measurements are currently unreliable and produce a significant amount of false positive and false negative. For example, pavement receiving a new wearing course after the FAST application is rated as severely raveled even though it is not. Surface texture is more accurately represented by the mean profile depth. Pothole is considered as a localized distress and typically the in-house field crew patches potholes based on the residents' requests. Surface deformation is to be captured by rutting using a taut wire method to be more conservative and recommended by the vendor for the urban environment.

Pavement cracks are detected and classified as fatigue crack, longitudinal wheel path, longitudinal non-wheel path, or transverse crack based on the crack orientation, density, and position within the 3-m (10-ft) analysis section. Since LCMS is Pavemetric's proprietary technology, it is unclear how these densities correlate to crack density in a moving plane or inventory area. Based on visual assessment and validated by measuring the size of the fatigue cracks mapped, low severity, medium severity, and high severity fatigue crack density ranges were set. Low density fatigue crack ranges from 0.9 to 1.2 while medium density ranges between 1.2 and 1.5 and high density is greater than 1.5. Figure 3-5 illustrates low fatigue cracking since cracks in the green rectangle area are a little sparser than cracks in the yellow rectangle in Figure 3-6 and red rectangle Figure 3-7. In Figure 3-6, fatigue cracks in the yellow rectangle represent medium severity fatigue crack while in Figure 3-7, fatigue cracks inside the red rectangle are densest and indicate the high severity fatigue crack. Therefore, fatigue cracking is defined by an area of interconnected cracks that form a complete pattern, irrespective of how and where the cracks are initiated or formed. The traditional fatigue cracking is initiated at the bottom of the asphalt surface or stabilized base and defined by a series of interconnected cracks occurring in the wheel path, the area subjected to the repeated traffic loading.

Cracks with density lower than 0.9 that did not fall into the fatigue density ranges are classified either as longitudinal crack or transverse crack. The severity of the longitudinal crack and transverse crack are rated based on the width of the crack opening. Cracks are rated as low when the crack width is less than 0.006 m (¼ in), medium when crack width is between 0.006 m (¼ in) and 0.019 m (¾ in), and high when crack width is larger than 0.019 m (¾ in). Transverse crack is oriented perpendicular to the direction of the travel as shown in Figure 3-8 while longitudinal crack is oriented parallel to the direction of travel and is illustrated in Figure 3-9.

Longitudinal cracks are further separated into the wheel path or non-wheel path depending on whether the crack is in the wheel path or outside of the wheel path.

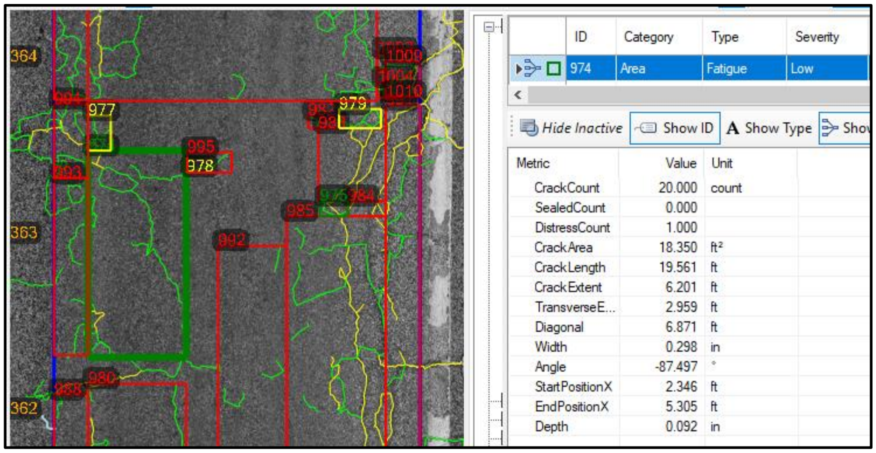


Figure 3-5: Low Severity Fatigue Crack Area Inside the Green Rectangle

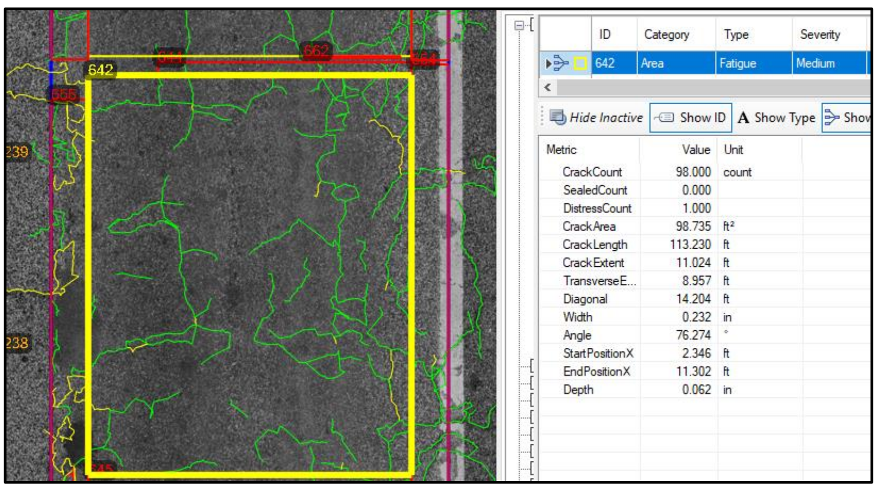


Figure 3-6: Medium Severity Fatigue Crack Area Inside the Yellow Rectangle

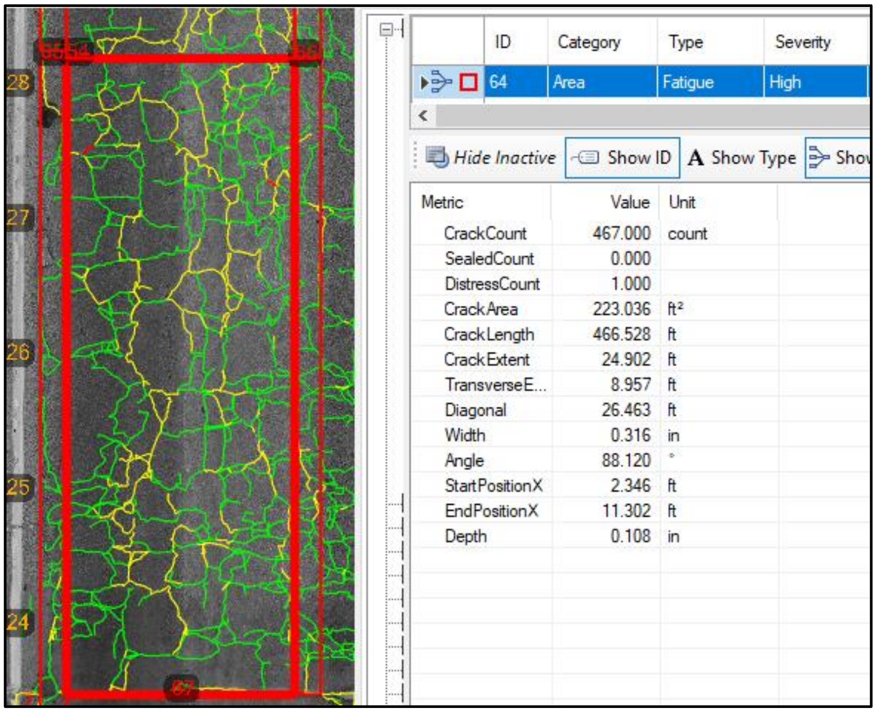


Figure 3-7: High Severity Fatigue Crack Area Inside the Red Rectangle

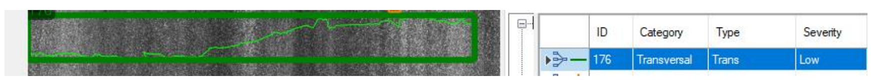


Figure 3-8: Transverse Crack

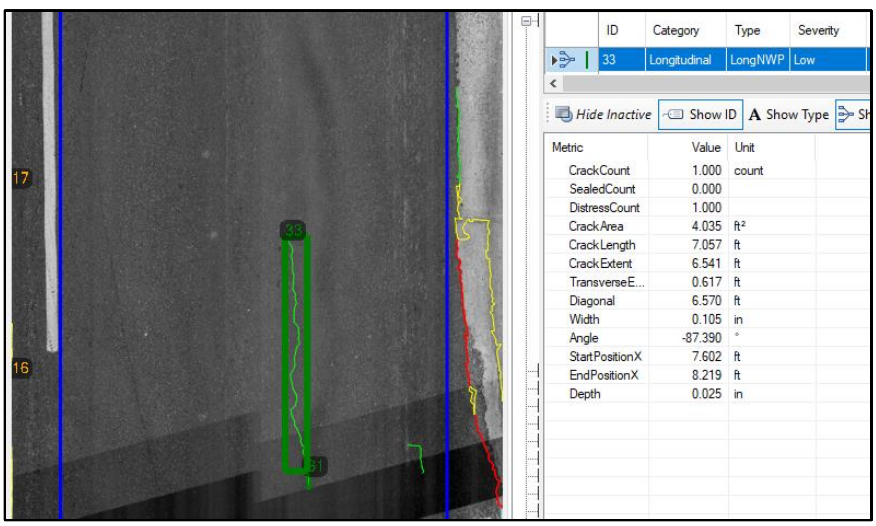


Figure 3-9: Longitudinal Non-Wheel Path Crack

3.4.3 Pavement Condition Index Calculation

Pavement Condition Index (PCI) is a numerical measure representing pavement condition and used at the City of Phoenix for the reporting purpose, not used in recommending treatment at the analysis stage. The City of Phoenix method of calculating pavement condition index (PCI) captures the surface conditions such as fatigue crack, longitudinal crack, transverse crack, and roughness of a pavement. A PCI of 100 represents pavement in excellent condition and 0 for very poor pavement needing a repair or reconstruction. The PCI range the City of Phoenix specifies, and its corresponding pavement condition description is shown in Figure 3-10.

Excellent	90-100
Good	70-89
Fair	45-69
Poor	20-44
Very Poor	0-19

Figure 3-10: City of Phoenix PCI Range

All pavement begins with a rating of 100 and depending on the distress detected on the pavement, points are deducted. The deduct values differ by the type, severity, and extent of distress quantified. For example, the deduct value for the street with 100% fatigue crack at high severity is 78.48, 57.19 at medium severity, and 39.01 at low severity. On the other hand, the deduct value for pavement roughness is calculated based on the IRI value. For IRI between 0 to 1.3 m/km (0 to 80 in/mi), the deduct value is 0 and for IRI greater than 3.8 m/km (240 in/mi), the deduct value is 100. Deduct charts for fatigue crack, longitudinal wheel path crack, longitudinal non-wheel path crack, transverse crack, and roughness are shown in Figure 3-11. The minimum value of any individual distress is zero (0) and is calculated using the equation:

$$Distress\ Index = 100 - Low\ Severity\ Deduct - Medium\ Severity\ Deduct - High\ Severity\ Deduct$$ Equation 3-1

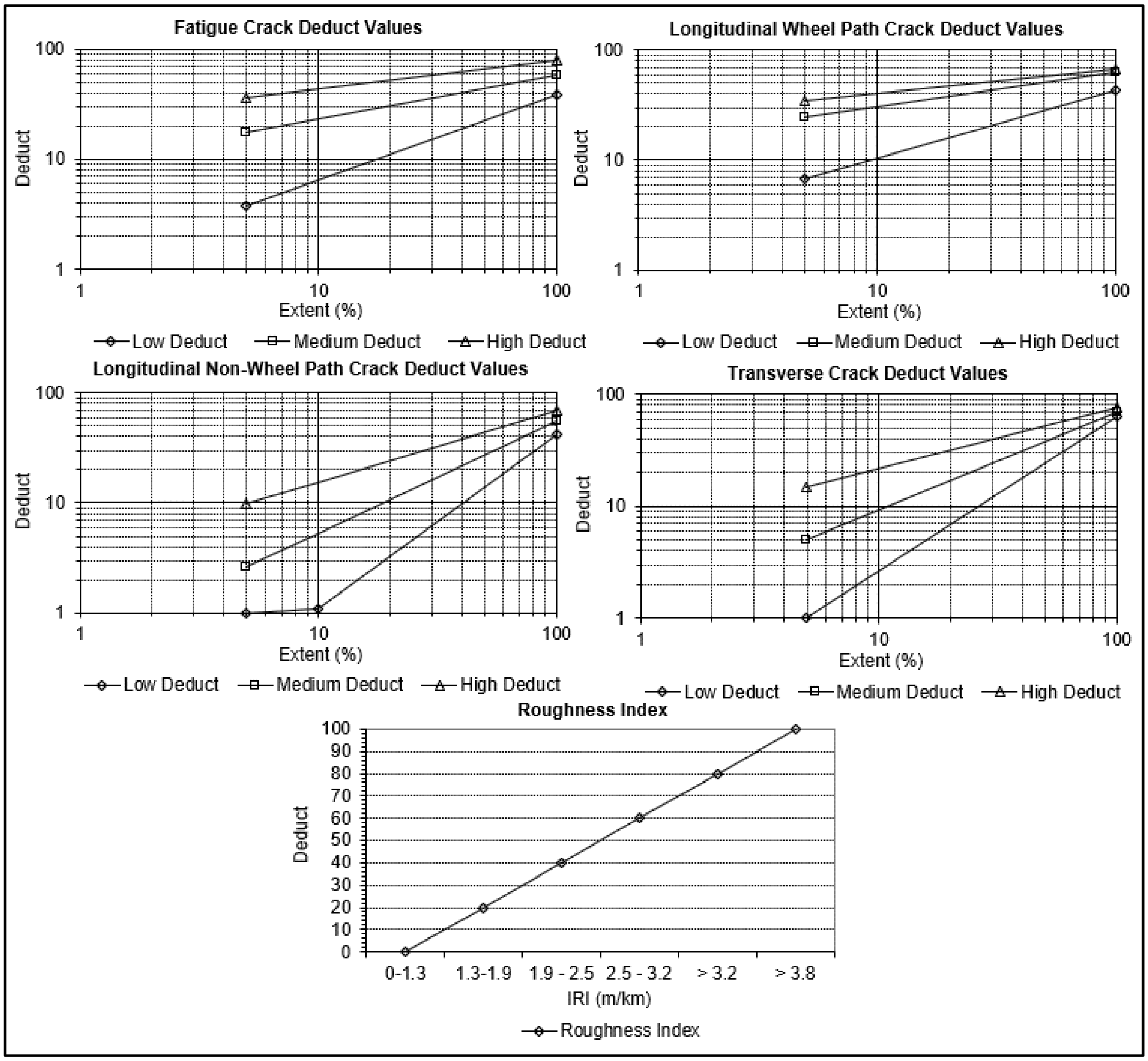


Figure 3-11: City of Phoenix Distress Deduct Charts by Distress Type, Severity, and Extent

Figure 3-12 illustrates how PCI is derived currently. The individual distress severity and extent data is exported to dTIMS and where deduct values are assigned to generate the individual distress index. Similar to the PCI concept, fatigue crack index of 100 means no fatigue crack was detected. Three composite indexes: structural, environmental and roughness conditions are computed by combining different distresses as indicated by Equations 3-1 through 3-3. The PCI formula is shown in Equation 3-4.

$$Structural\ Composite\ Index = \frac{Fatigue\ Crack\ Index + Longitudinal\ Wheel\ Path\ Crack\ Index}{2}$$ Equation 3-2

$$Environmental\ Composite\ Index = \frac{Longitudinal\ Non{-}Wheel\ Path\ Crack\ Index + Transverse\ Crack\ Index}{2}$$ Equation 3-3

$Roughness\ Composite\ Index = Roughness\ Index$ Equation 3-4

$PCI = 0.75 * \left(\frac{Structural\ Composite\ Index + Environmental\ Composite\ Index + Roughness\ Index}{3}\right) - Standard\ Deviation\ (Structural\ Composite\ Index + Environmental\ Composite\ Index + Roughness\ Index)$ Equation 3-5

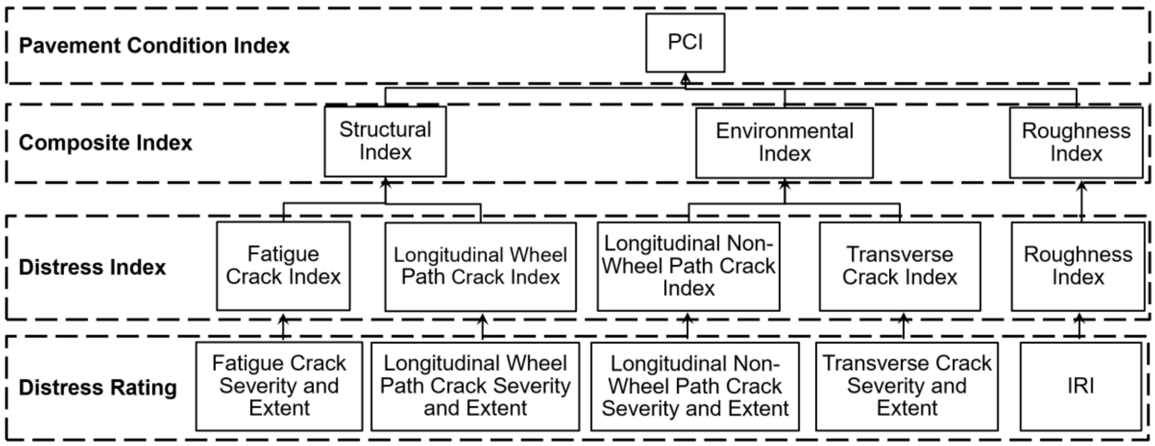


Figure 3-12: Current PCI Derivation

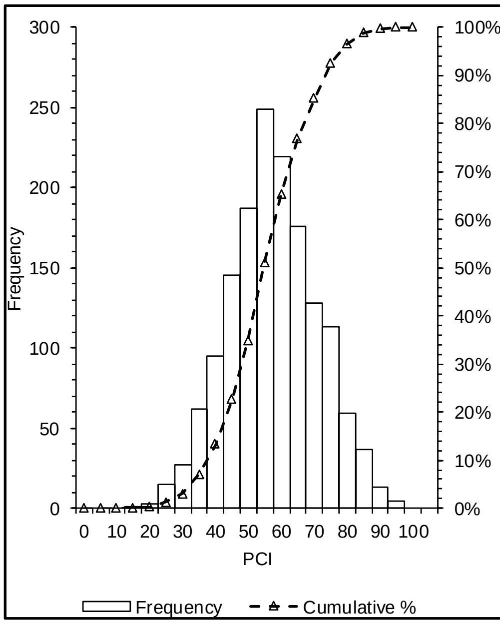
3.4.4 Pavement Condition Data

The pavement condition data analyzed is based on the 10% of the City of Phoenix's street network. A random selection of the network pavement condition is represented by 10% of each street classification in each council and is analyzed. There were 1533 sections analyzed and the council and the functional classification split are noted in Table 3-3. The overall City of Phoenix's street network PCI is at 55, the arterial street and collect street sub-network PCI is at 64 and residential and minor collector sub-network PCI is at 53. These PCIs fall in fair condition, with less than 0.5% of the street in excellent condition, approximately 17% in good condition, 62% in fair condition, 20% in poor condition, and 0.2% in very poor condition. Figure 3-13 shows PCI a normally distributed 10% of the City of Phoenix network which takes the shape of a normally distributed curve, with its peak at a PCI range between 50 and 55.

Table 3-3: Council District and Functional Classification Split of the 10% of City of Phoenix Street Network Analyzed

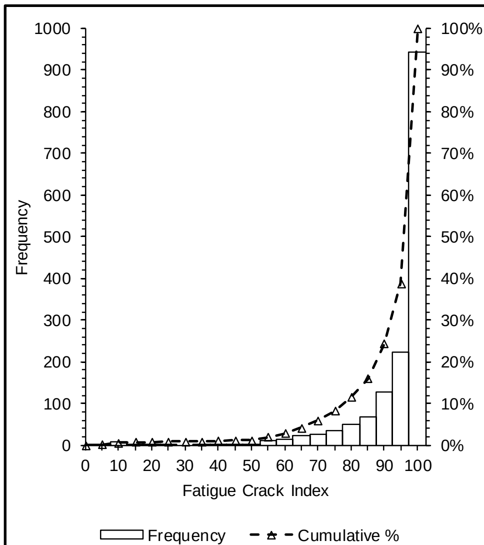
Council District	Street Classification					Total
	Arterial	Collector	Industrial	Major Collector	Residential	
1	34	5	4	141	16	200
2	31	4		171	14	220
3	28	3	2	165	13	211
4	26	5		130	8	169
5	18	2	6	122	9	157
6	35	7		151	13	206
7	37	4	11	114	13	179
8	31	7	19	119	15	191
Total	240	37	42	1113	101	1533

Figures 3-13 to 3-18 show histograms of 10% of the overall network individual distress indices currently considered in calculating PCI. The fatigue crack index, longitudinal non-wheel path crack index, and transverse crack index histograms are J-shaped while longitudinal wheel path crack index is almost normally distributed, and roughness index is normally distributed. Approximately 61% of the sections have fatigue crack index greater than 95, 72% of the sections have longitudinal non-wheel path crack index greater than 90, and 53% of the sections have transverse crack index greater than 85. Therefore, for these three distress indices, most of the streets have fatigue crack index, longitudinal non-wheel path crack index, and transverse crack index greater than 85. Most of the streets have a much lower longitudinal wheel path crack index and roughness index. Approximately 55% of the streets have longitudinal wheel path crack index less than 65 while approximately 51% of the streets have roughness index less than 55. Referring to the PCI equation 3-5, roughness index contribution to the PCI calculation is greatest.



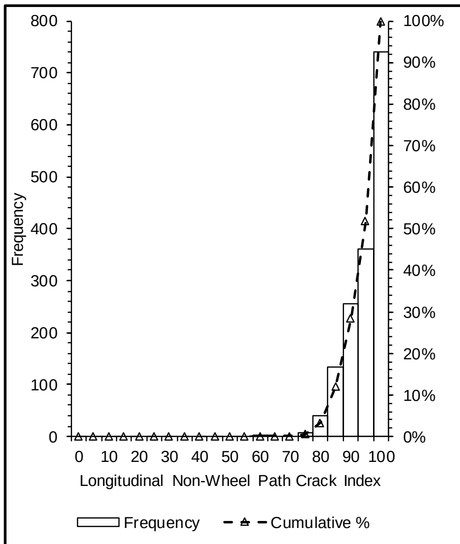
PCI	Frequency	Cumulative %
0	0	0.00%
5	0	0.00%
10	0	0.00%
15	1	0.07%
20	3	0.26%
25	15	1.24%
30	27	3.00%
35	62	7.05%
40	95	13.24%
45	145	22.70%
50	187	34.90%
55	249	51.14%
60	219	65.43%
65	176	76.91%
70	128	85.26%
75	113	92.63%
80	59	96.48%
85	37	98.89%
90	13	99.74%
95	4	100.00%
100	0	100.00%

Figure 3-13: 10% Sample Street Network PCI



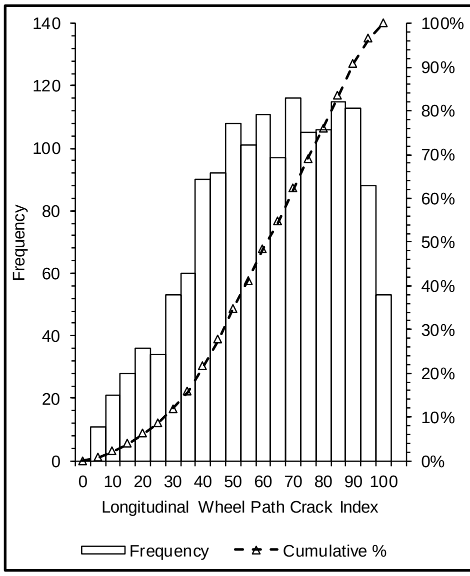
Fatigue Crack Index	Frequency	Cumulative %
0	0	0.00%
5	2	0.13%
10	7	0.59%
15	1	0.65%
20	2	0.78%
25	1	0.85%
30	0	0.85%
35	1	0.91%
40	2	1.04%
45	1	1.11%
50	2	1.24%
55	10	1.89%
60	14	2.80%
65	22	4.23%
70	26	5.92%
75	35	8.19%
80	51	11.51%
85	69	15.99%
90	127	24.25%
95	223	38.75%
100	942	100.00%

Figure 3-14: Sample Street Network Fatigue Crack Index



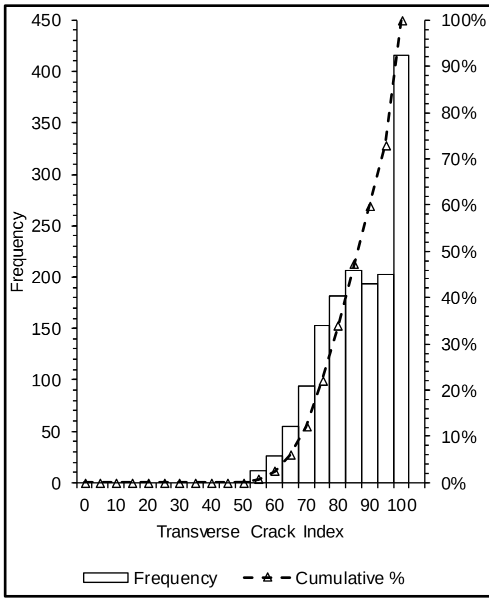
Longitudinal Non-Wheel Path Crack Index	Frequency	Cumulative %
0	0	0.00%
5	0	0.00%
10	0	0.00%
15	0	0.00%
20	0	0.00%
25	0	0.00%
30	0	0.00%
35	0	0.00%
40	0	0.00%
45	0	0.00%
50	0	0.00%
55	0	0.00%
60	1	0.07%
65	0	0.07%
70	0	0.07%
75	8	0.59%
80	41	3.25%
85	133	11.90%
90	255	28.48%
95	360	51.89%
100	740	100.00%

Figure 3-15: Sample Street Network Longitudinal Non-Wheel Path Index



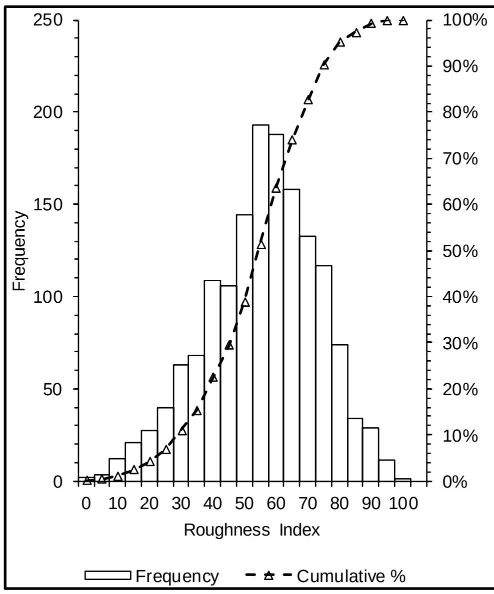
Longitudinal Wheel Path Crack Index	Frequency	Cumulative %
0	0	0.00%
5	11	0.72%
10	21	2.08%
15	28	3.90%
20	36	6.24%
25	34	8.45%
30	53	11.90%
35	60	15.80%
40	90	21.65%
45	92	27.63%
50	108	34.66%
55	101	41.22%
60	111	48.44%
65	97	54.75%
70	116	62.29%
75	105	69.12%
80	106	76.01%
85	115	83.49%
90	113	90.83%
95	88	96.55%
100	53	100.00%

Figure 3-16: 10% Sample Street Network Longitudinal Wheel Path Index



Transverse Crack Index	Frequency	Cumulative %
0	0	0.00%
5	0	0.00%
10	0	0.00%
15	0	0.00%
20	0	0.00%
25	0	0.00%
30	0	0.00%
35	0	0.00%
40	0	0.00%
45	0	0.00%
50	1	0.07%
55	11	0.78%
60	26	2.47%
65	55	6.05%
70	94	12.16%
75	153	22.11%
80	181	33.88%
85	206	47.27%
90	193	59.82%
95	202	72.95%
100	416	100.00%

Figure 3-17: 10% Sample Street Network Transverse Index



Roughness Index	Frequency	Cumulative %
0	2	0.13%
5	3	0.33%
10	12	1.11%
15	21	2.48%
20	27	4.24%
25	40	6.85%
30	63	10.96%
35	68	15.39%
40	109	22.50%
45	106	29.42%
50	144	38.81%
55	193	51.40%
60	188	63.67%
65	158	73.97%
70	133	82.65%
75	117	90.28%
80	74	95.11%
85	34	97.33%
90	29	99.22%
95	11	99.93%
100	1	100.00%

Figure 3-18: 10% Sample Street Network Roughness Index

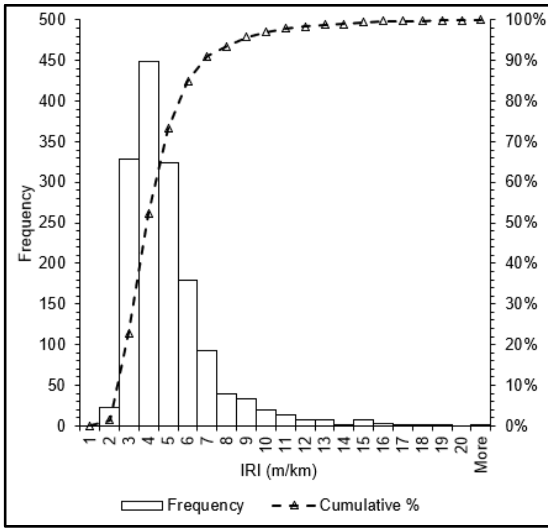
Since the roughness index is derived from IRI, IRI is further investigated. The City of Phoenix has been using the automated data collection method to collect pavement surface distresses such as cracks and roughness since the city purchased its first ARAN in 2008. Although the International Roughness Index (IRI) has been used as a road roughness index on highways for well over three decades, variation of speed and lower vehicle speed on local streets adversely affect the roughness indicator, IRI data quality.

The IRI of the 10% of the overall street network, 10% of non-residential streets, and 10% of residential streets were evaluated. Residential streets are evaluated separately since the speed on the residential street is lower. Figure 3-19 to 3-21 show IRI histograms of the overall street network, non-residential streets, and residential streets. The shapes of these three histograms are similar and are right skewed. Referring to Figure 3-11, the deduct value for IRI greater than 3.8 m/km (240 in/mi) is 100 and subsequently the roughness index is 0 for IRI greater than 3.8 m/km (240 in/mi). 53% of the streets in the 10% of the overall street network have IRI greater than 3.8 m/km (240 in/mi). Although only 30% of the non-residential streets have IRI greater than 3.8 m/km (240 in/mi), 60% of the residential streets have IRI greater than 3.8 m/km (240 in/mi).

In a low-speed urban street network, the ARAN pavement inspection vehicle driver experiences challenges in maintaining 25 km/h (15.5 mph) and avoiding complex on-road maneuvers. Based on the field observation, IRI greater than 3.8 m/km (240 in/mi) on residential streets does not represent rough pavement. Passing and stop-and-go maneuvers to avoid parked cars, to safely stop at stop signs, signals, and crosswalk, and to slowly transverse across speed humps, valley gutters, and rail tracks, produce unreliable and unrepeatable IRI. The effects of factors such as the presence of the traffic calming device, speed hump, valley gutter, traffic circle, driveway, and the small roadway horizontal and vertical curves causing IRI to spike are represented in Figure 3-22. The right wheel path IRI is higher than the left wheel path IRI on Mountain View Rd between Central Ave and 7th St because of the variation in roadway cross slopes to tie to the cross streets and driveway accesses. Since even the slightest shift in driving behavior to avoid parked cars has been seen to affect the IRI, it is necessary to explore other means to measure pavement roughness. Roughness in roadway profile cannot be adequately corrected by preservation treatment, thus a more appropriate measure to collect is surface texture roughness and thus macrotexture indicator mean profile depth (MPD) is also investigated. Considering slurry sealed or micro sealed pavement has MPD around 1.0 mm (0.04 in) and low volume FAST around 1.2 mm (0.05 in), pavement having greater than MPD of 1.2 mm (0.05 in) can be considered as having rough surface texture. As shown in Figure 3-23 to Figure 3-25, 36%

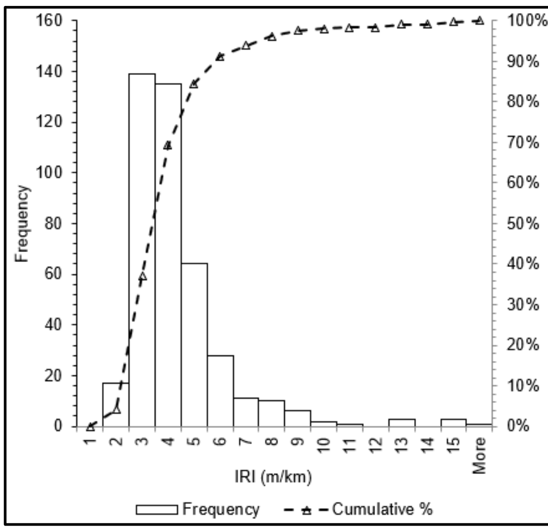
of the streets in the 10% of the overall street network, 27% of the non-residential streets, and 40% of the residential streets have MPD greater than 1.2 mm.

Rut is a depression along the wheel path and a mean rut depth less than 13 mm (0.5 in) is considered a low severity level rut according to ASTM D6433. Although there are localized rut areas, it is not a major problem observed in the city's street network that it is not considered in the pavement management system. As shown in Figure 3-26, 2% streets in the network have rut depth greater than 6 mm (0.25 in) and no street with rut depth greater than 13 mm (0.5 in).



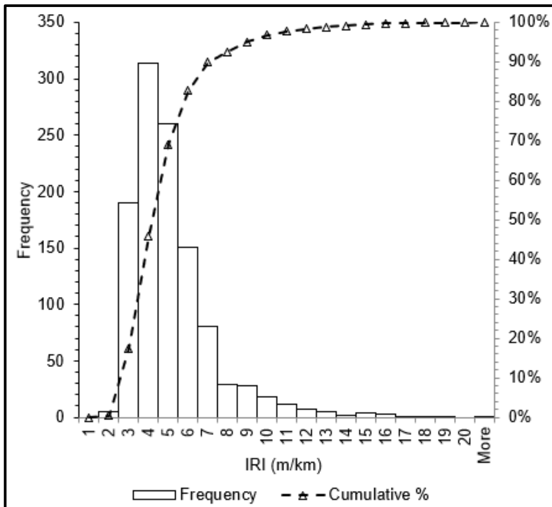
IRI (m/km)	Frequency	Cumulative %
1	0	0.00%
2	22	1.44%
3	329	22.90%
4	449	52.19%
5	324	73.32%
6	179	85.00%
7	92	91.00%
8	39	93.54%
9	34	95.76%
10	20	97.06%
11	13	97.91%
12	7	98.37%
13	8	98.89%
14	2	99.02%
15	7	99.48%
16	3	99.67%
17	1	99.74%
18	1	99.80%
19	2	99.93%
20	0	99.93%
More	1	100.00%

Figure 3-19: 10% Sample Street Network IRI (m/km)



IRI (m/km)	Frequency	Cumulative %
1	0	0.00%
2	17	4.05%
3	139	37.14%
4	135	69.29%
5	64	84.52%
6	28	91.19%
7	11	93.81%
8	10	96.19%
9	6	97.62%
10	2	98.10%
11	1	98.33%
12	0	98.33%
13	3	99.05%
14	0	99.05%
15	3	99.76%
More	1	100.00%

Figure 3-20: Non-Residential Streets IRI (m/km)



IRI (m/km)	Frequency	Cumulative %
1	0	0.00%
2	5	0.45%
3	190	17.52%
4	314	45.73%
5	260	69.09%
6	151	82.66%
7	81	89.94%
8	29	92.54%
9	28	95.06%
10	18	96.68%
11	12	97.75%
12	7	98.38%
13	5	98.83%
14	2	99.01%
15	4	99.37%
16	3	99.64%
17	1	99.73%
18	1	99.82%
19	1	99.91%
20	0	99.91%
More	1	100.00%

Figure 3-21: Residential Streets IRI (m/km)

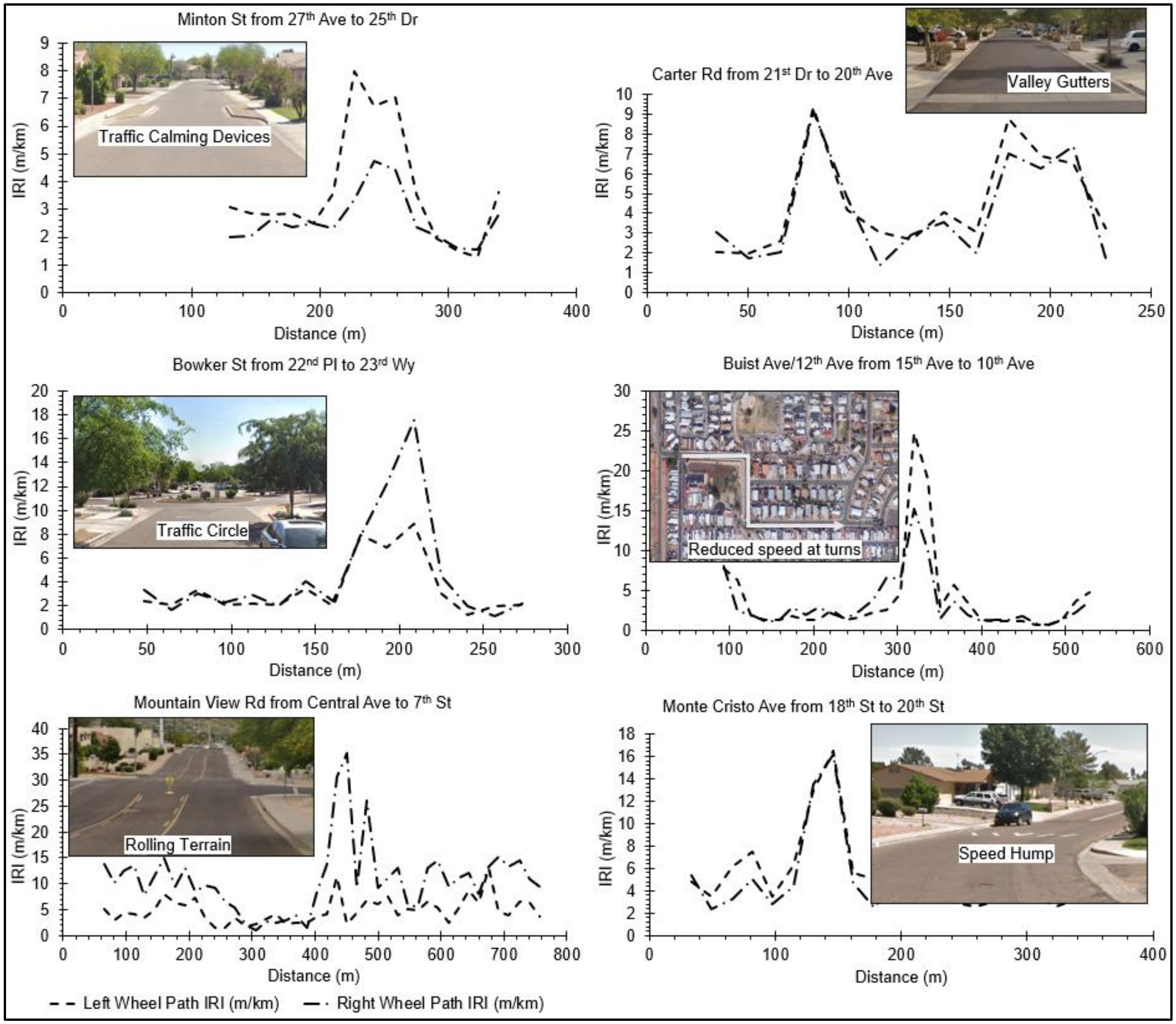
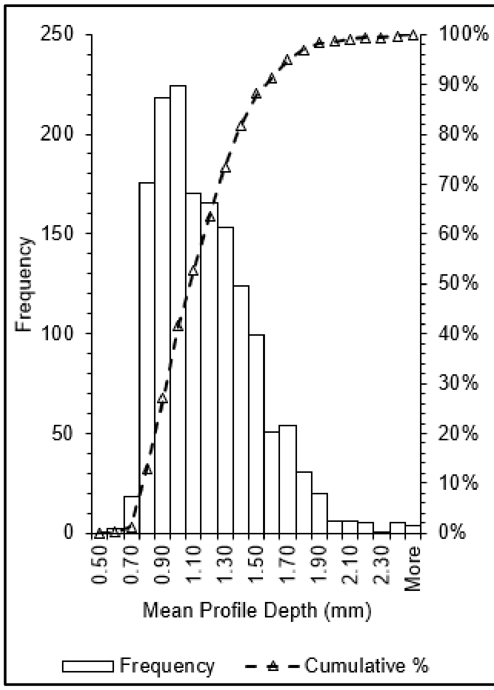
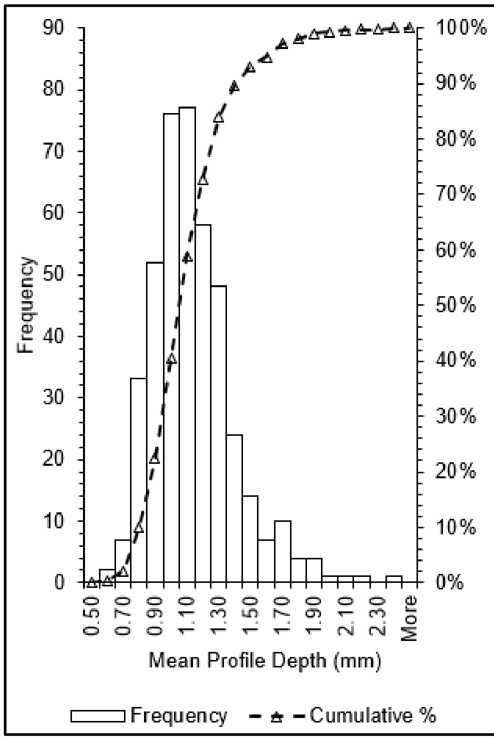


Figure 3-22: Factors Affecting IRI



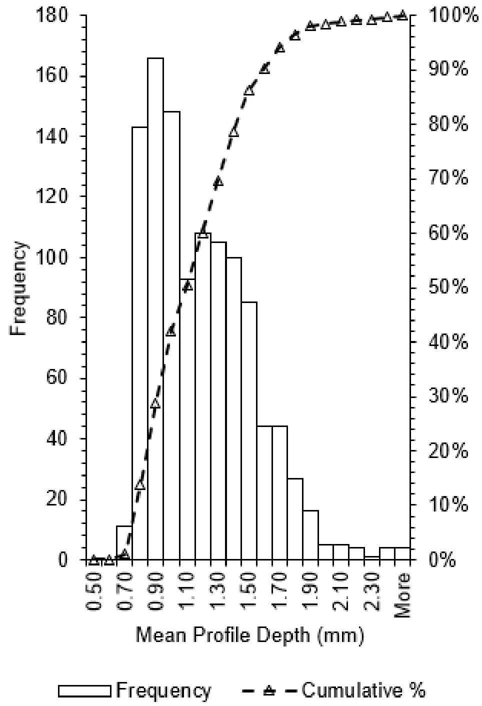
MPD (mm)	Frequency	Cumulative %
0.50	0	0.00%
0.60	2	0.13%
0.70	18	1.30%
0.80	176	12.79%
0.90	218	27.01%
1.00	224	41.62%
1.10	170	52.71%
1.20	166	63.54%
1.30	153	73.52%
1.40	124	81.60%
1.50	99	88.06%
1.60	51	91.39%
1.70	54	94.91%
1.80	31	96.93%
1.90	20	98.24%
2.00	6	98.63%
2.10	6	99.02%
2.20	5	99.35%
2.30	1	99.41%
2.40	5	99.74%
More	4	100.00%

Figure 3-23: 10% Sample Street Network Mean Profile Depth (mm)



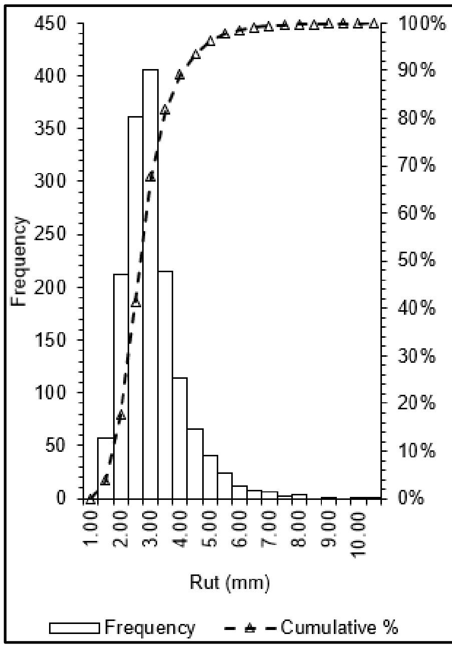
MPD (mm)	Frequency	Cumulative %
0.50	0	0.00%
0.60	2	0.48%
0.70	7	2.14%
0.80	33	10.00%
0.90	52	22.38%
1.00	76	40.48%
1.10	77	58.81%
1.20	58	72.62%
1.30	48	84.05%
1.40	24	89.76%
1.50	14	93.10%
1.60	7	94.76%
1.70	10	97.14%
1.80	4	98.10%
1.90	4	99.05%
2.00	1	99.29%
2.10	1	99.52%
2.20	1	99.76%
2.30	0	99.76%
2.40	1	100.00%
More	0	100.00%

Figure 3-24: Non-Residential Streets Mean Profile Depth (mm)



MPD (mm)	Frequency	Cumulative %
0.50	0	0.00%
0.60	0	0.00%
0.70	11	0.99%
0.80	143	13.84%
0.90	166	28.75%
1.00	148	42.05%
1.10	93	50.40%
1.20	108	60.11%
1.30	105	69.54%
1.40	100	78.53%
1.50	85	86.16%
1.60	44	90.12%
1.70	44	94.07%
1.80	27	96.50%
1.90	16	97.93%
2.00	5	98.38%
2.10	5	98.83%
2.20	4	99.19%
2.30	1	99.28%
2.40	4	99.64%
More	4	100.00%

Figure 3-25: Residential Streets Mean Profile Depth (mm)



Rut (mm)	Frequency	Cumulative %
1.00	0	0.00%
1.50	58	3.78%
2.00	212	17.61%
2.50	362	41.23%
3.00	406	67.71%
3.50	215	81.74%
4.00	114	89.17%
4.50	66	93.48%
5.00	41	96.15%
5.50	25	97.78%
6.00	12	98.56%
6.50	8	99.09%
7.00	6	99.48%
7.50	2	99.61%
8.00	3	99.80%
8.50	0	99.80%
9.00	1	99.87%
9.50	0	99.87%
10.00	1	99.93%
More	1	100.00%

Figure 3-26: 10% Sample Street Network Rut (mm)

3.5 PMS ANALYSIS PARAMETERS

3.5.1 Pavement Maintenance Needs

Pavement maintenance needs are dependent on the pavement condition. Based on the 2020 pavement condition collection year dataset which comprised data collected between December 6, 2017 and August 4, 2020, Phoenix's street network PCI is 63 representing a "fair" condition and nearing the "good" range. As shown in Table 3-4, 92% of the Phoenix street network, 94% of the arterial and major collector sub-network, and 91% of the residential and minor collector sub-network are in fair or better condition. As per City of Phoenix treatment guidelines, pavement in fair and better conditions are appropriate for preservation treatments. Therefore, an effective preservation treatment program can preserve and extend the life of the City of Phoenix street network.

Table 3-4: Phoenix Street Network Pavement Condition Rating

PCI Range	Rating	Phoenix Street Network	Arterial and Major Collector Sub-Network	Residential and Minor Collector Sub-Network
90-100	Excellent	4%	1%	5%
70-89	Good	58%	60%	58%
45-69	Fair	30%	33%	28%
20-44	Poor	6%	6%	7%
0-19	Very Poor	2%	0%	2%

Table 3-5 provides guidelines the City of Phoenix uses in recommending preservation treatments. The dTIMS analyzes the pavement condition data and recommends a preservation treatment based on the latest pavement condition data. The City of Phoenix uses preservation treatments to mitigate fatigue cracking, longitudinal wheel path cracking, longitudinal non-wheel path cracking, transverse cracking, and roughness. All projects undergo field inspection to verify that the dTIMS recommended treatment is appropriate. Fog seals and seal coats are applied on pavement in excellent and good condition to mitigate transverse cracking, longitudinal cracking, and fatigue cracking. The slurry seal and micro seal are applied on pavement in good and fair condition to mitigate transverse cracking, longitudinal cracking, and fatigue cracking. FAST is applied on pavement in fair and poor condition to mitigate longitudinal cracking and fatigue cracking. Thin overlay is applied on pavement in fair and poor condition to mitigate transverse cracking, longitudinal cracking, and fatigue cracking.

Table 3-5: City of Phoenix Preservation Treatment Guidelines

Pavement Distress	City of Phoenix Preservation Treatments			
	Fog Seal/ Seal Coat	Slurry Seal/ Micro Seal	FAST	Thin Overlay
	Condition Rating			
	Excellent / Good	Good / Fair	Fair / Poor	Fair / Poor
Roughness				x
Transverse Cracking	x	x		x
Longitudinal Non-Wheel Path Cracking	x	x	x	x
Longitudinal Wheel Path Cracking	x	x	x	x
Fatigue Cracking	x	x	x	x

3.5.2 Pavement Performance Model

The historical pavement condition data can be used to test the reasonableness of the pavement performance models and the expert opinions can be used in the meantime while a more detailed evaluation can be performed in the future for agencies that do not yet have historical data. At a minimum, a set of historical data for a representative sample of the network for several different surface types and a range of pavement conditions with at least three data points and covering the span of treatment design life is desirable in validating the performance model to predict the pavement condition 3, 5, and 10 years out in the future. By comparing the predicted results to the actual conditions recorded during a pavement condition survey, an agency can assess the reasonableness of the forecasts at each point in time. However, since the City of Phoenix does not have condition data available to validate the model, a field evaluation of the 2021 fog seal program was performed to determine how well the pavement performance model predicts and how accurately it projects the treatment for the future pavement needs.

Appendix A documented 79 fog seal project locations, treatments recommended by the engineers based on field evaluation performed in June 2020, and their explanations for upgrading treatments. 50 of the programmed treatment locations remained the same, while 20 locations were upgraded to receive micro seal or slurry seal mainly based on the rough surface texture observed during the field reevaluation. 1 location was upgraded from fog seal to FAST and 8 locations were upgraded to thin overlay mainly based on the extent of fatigue cracking observed in the pavements. A total of 29 fog seal projects which is more than a third of the 2021 program required treatment upgrades to address the actual needs at the year of the treatment program. This indicates that the performance model predicting the performance of the pavement three years out in the future needs to be updated to better reflect field deterioration rate. Since the final treatment recommendation is made by the engineers, while reviewing PMS recommended locations, the engineers are recommended to forecast the pavement deterioration more aggressively especially in areas where water intrusion and heavy construction activities are expected.

3.5.3 Preservation Treatment Trigger

The analysis was performed independently for the arterial and major collector sub-network and the residential and minor collector sub-network. Thus, there are two sets of conditions to trigger maintenance treatment. Table 3-4 shows maintenance treatment triggers currently in place for the residential and minor collector street network and Table 3-5 shows triggers for the arterial and major collector street sub-network. The city of Phoenix PMS treatment selection process first considers the age of the pavement since the last overlay or heavier treatment or new construction. Then the most current pavement condition data is used to calculate individual distress indices. The average condition of the pavement sections grouped by the super sections or quarter sections are used for the analysis. “Super section” or “quarter section” conditions which fall within the lower and upper bound of individual distress index such as fatigue crack index, longitudinal wheel path crack index, longitudinal non-wheel path crack index, transverse crack index, or roughness index, are considered to receive the recommended treatment. However, the final treatment recommendation and selection to become a project and receive a specified preservation treatment is dependent on the budget and the field review by engineers.

Table 3-6: Current Preservation Treatment Trigger for Local and Minor Collector Street Sub-Network

Treatment Name	Years Since Last Thin Overlay		Fatigue Crack Index		Longitudinal Wheel Path Crack Index		Longitudinal Non-Wheel Path Crack Index		Roughness Index		Transverse Crack Index	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Fog Seal	12		80	95	80	95	80	95			80	95
Seal Coat	12		80	95	80	95	80	95			80	95
Slurry Seal	19		70	80	25	75	25	75			25	75
FAST	12		30	70	45	80	45	80				
Thin Overlay	27		0	65	0	45	0	45	0	40	0	45

Table 3-7: Current Preservation Treatment Trigger for Arterial and Collector Street Sub-Network

Treatment Name	Years Since Last Thin Overlay		Fatigue Crack Index		Longitudinal Wheel Path Crack Index		Longitudinal Non-Wheel Path Crack Index		Roughness Index		Transverse Crack Index	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Fog Seal	12		80	95	80	95	80	95			80	95
Microseal	27		40	75	40	75	40	75			40	75
Thin Overlay	42		30	65	0	65	0	65	0	40	0	65

An evaluation of the current preservation treatment trigger is performed by comparing the treatment recommended by the PMS analysis and the treatment recommended by the engineers for the fiscal year 2024 program. The evaluation considered 84 super sections of the arterial and collector street sub-network and 221 super sections or quarter sections from the local and minor collector street sub-network. The PMS analysis data was performed using the fiscal year 2020 condition data collected by the new ARAN van between December 2017 and June 2020. Since 30 sections from the local and minor collector street sub-network were missing from the fiscal year 2020 condition dataset, previous years condition data were used for the analysis. A comparison of PMS recommended treatments and engineers' field recommendations for the arterial and collector street sub-network and for the local and minor collector street sub-network is represented in Appendix B. PMS recommended treatment and engineer's recommended treatment were the same for 30 locations out of 84 for the arterial and collector street sub-network and 106 out of 221 for the local and minor collector street sub-network. The treatment recommended by the PMS analysis differs from the engineer's field review performed in the summer of 2020 by more than 50% thus the current trigger setting needs to be revised. There were 36% of locations from the arterial and collector street sub-network and 40% from the local and minor collector street sub-network that PMS recommended treatment need to be downgraded to reflect the field projected treatment needs. In addition to revising the current treatment triggers, a high percent of super sections or quarter sections calls for reevaluation of distress deduct values as the new van can pick up fatigue cracks that were missing from the old van. The deduct values for the distresses were established based on the old van capabilities and are no longer compatible. There were 29% of locations from the arterial and collector street sub-network and 12% from the local and minor collector street sub-network that PMS treatment selection needs to be upgraded to reflect the field projected treatment needs. Further investigation of these sections shows that the fatigue cracking index for these sections does not accurately represent the field condition. Additionally, PMS analysis neglects to consider the rough surface texture and the effects of combined distresses. Therefore, the treatment recommendation was unsatisfactory.

A field review of 70 sections from the residential and minor collector street sub-network and 33 sections from the arterial and collector street sub-network were performed and preservation treatments were recommended based on the pavement condition at the time of the review. Firstly, the pavement section needs to fall into the specified pavement age since the last overlay or heavier treatment or new construction before individual pavement indices are considered. Figure 3-27 and Figure 3-28 show tentative maintenance treatment triggers for the local and minor collector street network and arterial and major collector street network respectively. Individual distress index range for a treatment is to be met to trigger a maintenance activity. Since the maintenance program is not for the year of the pavement condition data collection year but for the four years out in the future, how that pavement deterioration will deteriorate needs to be evaluated and the treatment trigger needs to be reevaluated based on the projected condition. Field verification and budget analysis will however supersede software treatment recommendations.

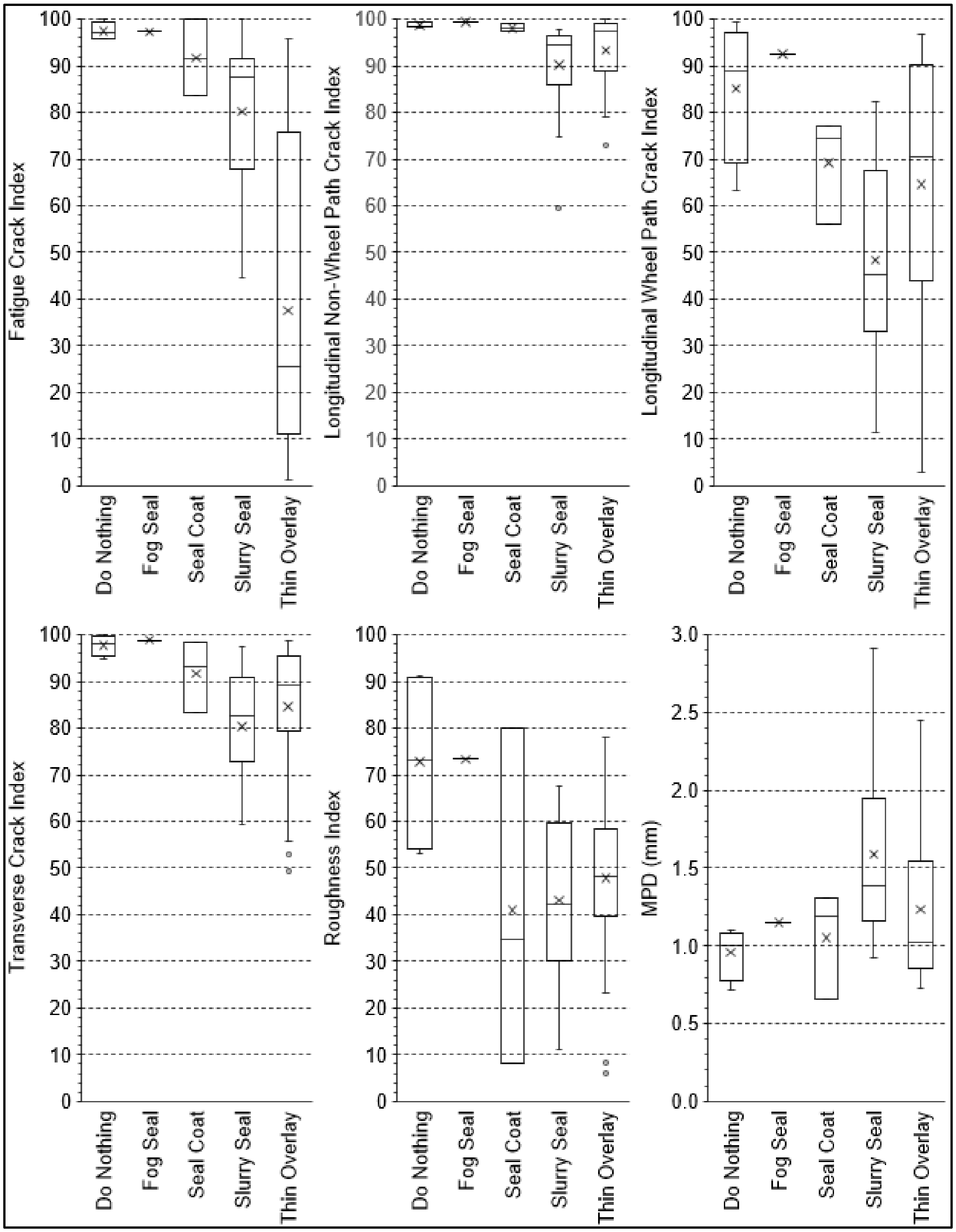


Figure 3-27: Tentative Maintenance Treatment Trigger Range for Residential and Minor Collector Street Sub-Network

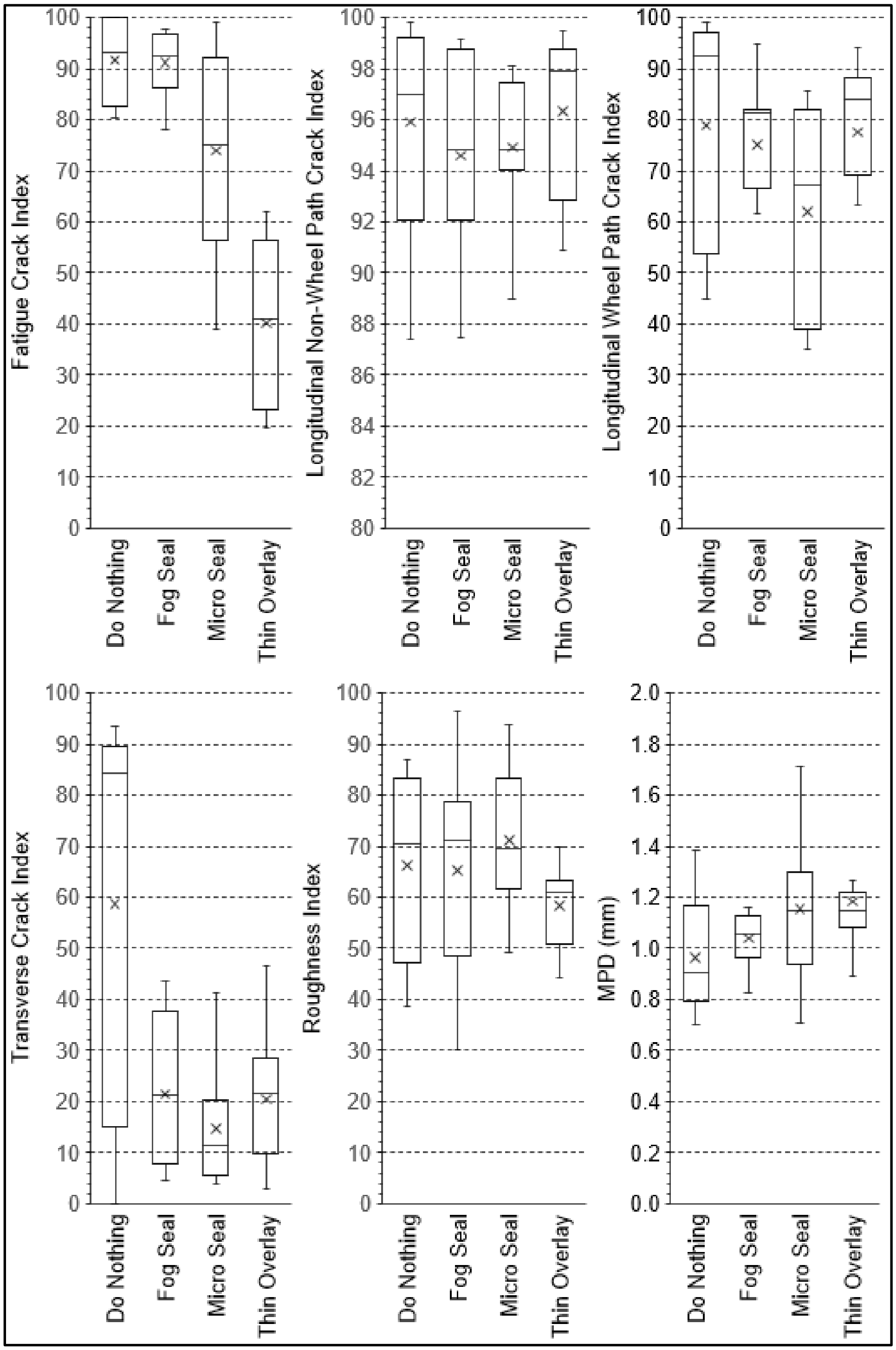


Figure 3-28: Tentative Maintenance Treatment Trigger Range for Arterial and Collector Street Sub-Network

A new treatment trigger cannot be developed as part of this study due to the data availability. The City of Phoenix can, however, test the reasonableness of the treatment trigger by generating a list of recommended treatments for the pavement network with different surface types and pavement conditions. A wide range of pavement conditions ensures a good representation of treatment types for the PMS to generate treatment recommendations and that there are no gaps in the treatment rules. The City of Phoenix can verify the treatment recommendation provided by dTIMS by performing a field review and evaluate whether the treatment recommended is appropriate.

3.5.4 Preservation Treatment Reset Values

The reset values are a critical component in determining treatment effectiveness and optimizing treatment strategies. The reset values after treatments are defined for each individual distress index using the model developed by the Deighton asset management team. Since the reset formula was proprietary information, no additional information other than the age reset values after treatment were available. The reset age after fog seal is 3 years, after slurry seal is 5 years, after micro seal is 7 years, after FAST is 10 years and after thin overlay is 12 years. A review of an improvement in the pavement condition index after treatment was performed based on the fiscal year 2020 committed projects. The projected PCI after the thin overlay treatment is 100 irrespective of the sub-network. The PCI jump after the micro seal application ranges from 3 to 32 and 1 to 8 PCI after fog seal for the arterial and major collector network. The improvements after slurry seal range from no improvement to 8 PCI jump. The improvements after FAST range from no improvement to 11 PCI. The PCI jump after fog seal/seal coat ranges from 1 to 8 for the residential and minor collector sub-network.

3.6 SUMMARY OF FINDINGS AND CONCLUSIONS

The City of Phoenix PMS lacks procedures to determine the effectiveness of applied preservation treatments and mechanisms to determine program effectiveness. The feedback which includes both individual pavement performance and overall treatment program performance will ensure PMS recommends treatments appropriately and allow performance models to be updated. An evaluation of the City of Phoenix’s non-technical and technical components of the pavement preservation program was performed. The network pavement performance evaluation was performed by evaluating 10% of the street network.

The major findings from this part of the study are highlighted below:

1. Overall, the city has a strong partnership with its street transportation stakeholders.
2. The efforts to collaborate with different departments and divisions can be improved by having pertinent data such as traffic count and maintenance and construction history be in sync with the PMS database rather than holding meetings to collect data.
3. The staffing of the pavement management team is lacking since the street network is very large and there is only one dedicated person to process and review pavement condition data.
4. Currently the city does not collect or use factors such as traffic and drainage and soil conditions that impact the pavement performance in PMS analysis.
5. Many private companies, departments, and divisions work in the street right of way, but only maintenance activities performed by the pavement maintenance sections are updated annually.
6. Pavement conditions in the urban network which is still growing and developing varies greatly, thus regrouping and redefining the pavement inventory sections was performed to avoid leaving out any untreated sections.
7. The upgrade to the new ARAN 9000 equipped with LCMS has a lot more capabilities than its predecessor.
8. Since LCMS is Pavemetric's proprietary technology, it was not possible to define the fatigue crack severity by the traditional method nor to differentiate fatigue cracking from block cracking.
9. FAST that is not raveled is rated as severely raveled by LCMS. Thus, mean profile depth is proposed as a performance indicator to measure pavement surface texture condition.
10. The fatigue crack index, longitudinal non-wheel path crack index, and transverse crack index are high indicating most of the pavements are in good condition.
11. The deduct values and the PCI equation need to be updated. The network PCI of 55 places the network in a fair condition. The low PCI is attributed by the roughness index which is overrated and by the longitudinal wheel path crack index.

12. 30% of the arterial network have IRI greater than 3.8 m/km (240 in/mi) and 60% of the residential network have IRI greater than 3.8 m/km (240 in/mi). In terms of roughness index, 30% of the arterial network and 60% of the residential network have a roughness index of 0 which is not a true representation of the City of Phoenix network.
13. Since IRI is affected by the travel speed and other factors, a more accurate and repeatable measure to represent pavement surface roughness was evaluated. Based on the macrotexture indicator MPD, MPD greater than 1.2 mm (0.05 in) is a rough textured pavement. Using the MPD threshold of 1.2 mm (0.05 in), 29% of the streets in the 10% of the overall street network, 17% of the non-residential streets, and 33% of the residential streets are found to be rough.
14. Rut is not an issue in the City of Phoenix network because there is no street section with an average rut depth greater than 1.2 mm (0.05 in).
15. Based on the 2020 pavement condition data, the health of the pavement is in fair condition with less than 8% of the network in poor condition, thus appropriate for preservation treatment.
16. The historical pavement condition data collected by the new ARAN van for at least three collection cycles are necessary to evaluate the pavement performance model, preservation treatment trigger, and preservation treatment reset values.

CHAPTER 4

A SIMPLIFIED PAVEMENT ASSESSMENT METHOD FOR PRESERVATION PROGRAM

4.1 INTRODUCTION

As many transportation agencies are taking on a holistic approach in managing their street network, the focus is on proactively maintaining or improving the condition of the pavement at the network level. Such an approach is supported by a cost-effective pavement preservation treatment program. Pavement preservation treatments sustain the condition of existing pavements by keeping them in good and structurally sound condition longer and enhancing the overall surface condition and rideability (Peterson, 1981). Based on their budget, agencies typically develop their annual pavement preservation treatment program a few years in advance of the actual treatment applications. Therefore, planning the right treatment on the right pavement at the right time is the key to a successful implementation of a pavement preservation program. Thin overlay, slurry seal, crack seal, and chip seal are effective and widely used preventive maintenance treatments (Jia, et al., 2020). This research considers thin overlay, chip seal, and slurry seal. Thin overlay is a dense-graded hot-mix asphalt concrete layer less than 38 mm thick. It is applied on existing pavement to provide a new wearing surface course, retard raveling, restore friction loss, and seal surface from moisture and oxidation. Chip seal is an application of an asphalt binder followed immediately by the spreading of cover material, chip, and rolled before the asphalt binder sets (Elkins, Thompson, Ostrom, & Visintine, 2018). Chip seals treat existing pavement in good condition with low friction, minor non-load-associated cracking, raveling, and oxidation. Chip seals are commonly used on low volume roads as a wearing course. Slurry seal is a homogenous mixture of asphalt emulsion, well-graded fine aggregate, water, and mineral filler (Elkins, Thompson, Ostrom, & Visintine, 2018). Slurry seal is spread over existing pavements to fill surface defects as a wearing course.

Since the functions of each type of preservation treatment are unique, the surface condition of the existing pavement is one of the critical factors in the preservation treatment selection. Pavement condition assessment methods range widely from manual surveys to semi-automated to fully automated surveys. Pavement condition data quality and the cost to collect and analyze the data are contingent upon the pavement condition assessment method or the extensiveness of pavement distresses assessed and reported. Based on American Society for Testing and Materials (ASTM) standard D6433 (ASTM D6433-20, 2020), during a visual survey of a sample unit, the type, severity, and extent of nineteen types of flexible pavement distresses are assessed to determine pavement condition index (PCI). These distresses can be grouped into three major categories: surface cracking, surface texture, and surface deformation. Alligator cracking, block cracking, longitudinal and transverse cracking, edge cracking, joint reflection cracking, and slippage cracking can be categorized as surface cracking. Surface texture considers distresses such as bleeding, polished aggregate, and weathering/raveling. Distresses such as patching and utility cut patching, potholes, bumps and sags, corrugation, depression, lane/shoulder drop off, railroad crossing, rutting, shoving, and swell can be grouped as surface deformation.

Objective and reliable pavement condition data collected over time is used to determine the performance of pavement over the life of the existing pavement. During the life of the pavement, there is a specific timing or existing pavement condition at which the maximum benefit from the preservation treatment can be achieved. A research study conducted by Elwardany et al., demonstrated the effectiveness of thin overlay treatment decreases as pavement condition prior to the application worsens while a greater extension in pavement service life is achieved when treatment is applied to pavement still in good condition (Elwardany, et al., 2018). Moreover, Ozer et al. study concluded that the effect of the existing pavement condition on the deterioration rate of the treated pavement is much more "pronounced" than the effects of traffic and truck percentage (Ozer, Ziyadi, & Faheem, 2018). The added benefit from a preservation treatment application is the difference in the measure of pavement performance over time between the treated and untreated pavement. Based on the benefit and costs analysis, Peshkin et. al described the optimal time to apply a treatment as the most effective timing scenario which provides the greatest improvement in condition at the lowest cost yielding the highest benefit to cost ratios (Peshkin, Hoerner, & Zimmerman, 2004).

Since it is costly and labor intensive for agencies to assess pavement distress data, the primary goal of this research was to recommend a simple yet measurable and trackable pavement functional performance indicator for flexible pavements. This indicator needs to represent the overall pavement condition, reflects the effects of a preservation treatment on pavement condition by the changes in condition indicator, and is simple for agencies to measure. The secondary goal of the research was to develop a pavement preservation treatment decision matrix to assist in implementing preservation treatment programs. The decision matrix considers the concept of optimal timing and long-term effectiveness of preservation treatments.

4.2 RESEARCH METHODOLOGY

This portion of the research study considers several components of a network-level pavement management system (PMS), including data analysis, pavement performance model, and treatment recommendation. The research methodology included the following:

1. Review historical pavement condition and construction and maintenance history.
2. Remove incomplete, erroneous, inaccurate, or unusual pavement condition data.
3. Identify a pavement distress indicator that is simple yet provides an accurate representation of the overall pavement condition.
4. Validate the viability of using the proposed simple pavement performance indicator to perform PMS analysis for the preservation program.
5. Develop pavement performance curves for original hot-mix dense graded asphalt pavements without any maintenance, thin overlay, chip seal, and slurry seal.
6. Establish optimal timing for preservation treatment.
7. Develop a decision tree for preservation treatment selection.

4.3 PAVEMENT PERFORMANCE CONDITION INDICATORS

While Wolters et al. (2011) noted pavement condition data quantity and data quality supporting decisions and necessary for reporting as critical factors in the selection of condition assessment method, Peterson (1987) emphasized the importance of repeatable pavement condition assessment procedure to measure and monitor the performance characteristics pertinent in pavement management system (PMS). Pavement distresses assessed manually were downloaded from the Long-Term Pavement Performance (LTPP) InfoPAVE database and MnROAD database from the Minnesota Department of Transportation and were used to determine PCI in accordance with ASTM standard D6433. There were 7,354 LTPP data points for 1,693 unique sections with a historical PCI rating between 70 and 100 collected between August 5, 1988 and October 08, 2019. There were 1,334 MnROAD data points for 182 unique sections with a historical PCI rating between 70 and 100 collected between October 15, 2003, and December 04, 2019. Based on ASTM's PCI numerical rating, pavements in satisfactory and good conditions suitable for preservation treatments fall between PCI of 70 and 100.

The relationships between the overall pavement condition, attributed by 19 types of flexible pavement distresses, and three major distress categories: surface cracking, surface texture, and surface deformation were investigated. Applying the same ASTM D6433 method used to calculate PCI for the asphalt pavement, surface cracking index (SCI), surface texture index (STI), and surface deformation index (SDI) were calculated by considering only the severity and extent of distress in each category. SCI is calculated by considering distress types such as alligator cracking, block cracking, longitudinal and transverse cracking, edge cracking, joint reflection cracking, and slippage cracking. STI is calculated by considering distress types such as bleeding, polished aggregate, and weathering/raveling. SDI is calculated by considering distress types such as patching and utility cut patching, potholes, bumps and sags, corrugation, depression, lane/shoulder drop off, railroad crossing, rutting, shoving, and swell.

LTPP dataset and MnROAD dataset were used to establish the relationship between PCI and SCI, STI, and SDI. The multiple regression analysis to identify and model the relationship between the dependent variable, predicted PCI ($PCI_{Predicted}$), and independent variables: SCI, STI, and SDI were performed using linear regression and ridge regression methods. Since the site-specific performance models provided the most reliable prediction compared to mechanistically based models and empirical based models (Hajek, Phang, Prakash, & Wrong, 1985), a separate ridge regression equation was developed for each of the dataset. Table 4-1 provides the results from linear and ridge regression analysis for LTPP and MnRoad dataset. The penalty term, λ, of 0.00024 for LTPP dataset and 0.00077 for MnROAD dataset yielding the smallest cross-validation error were selected for ridge regression analysis. An excellent correlation between the calculated PCI and $PCI_{Predicted}$, with R^2 of 0.98 for the LTPP dataset and R^2 of 0.93 the MnROAD dataset, was observed for both linear and ridge regression methods. The coefficients and intercepts of the prediction models were very close, and the mean squared error for the linear regression method was negligibly smaller than the ridge regression method for each dataset. The linear regression prediction model for the LTPP dataset and MnROAD dataset for PCI range greater than 70 are captured by Equation 4-1 and Equation 4-2 respectively:

$$PCI_{Predicted} = 0.95 * SCI + 0.73 * STI + 0.62 * SDI - 130.05 \text{ for range: } PCI_{Predicted} \geq 70 \quad \text{Equation 4-1}$$

$$\mathrm{PCI_{Predicted}} = 0.72 * \mathrm{SCI} + 0.63 * \mathrm{STI} + 0.73 * \mathrm{SDI} - 111.98 \text{ for range: } PCI_{Predicted} \geq 70 \quad \text{Equation 4-2}$$

Table 4-1: Regression Analysis Results on Predicted Pavement Condition Index Models

Dataset	LTPP		MnROAD	
Regression Method	Linear	Ridge	Linear	Ridge
Intercept	-130.05	-130.00	-111.98	-111.85
Coefficient of SCI	0.95	0.95	0.72	0.72
Coefficient of STI	0.73	0.73	0.63	0.63
Coefficient of SDI	0.62	0.62	0.76	0.76
R^2	0.98	0.98	0.93	0.93
Mean Squared Error	1.81	1.81	3.53	3.53

The most dominant predictor was determined using the LASSO (Least Absolute Shrinkage and Selection Operator) regression method. LASSO regression was performed for the various values of the penalty term, λ. As λ increases, SDI was the first variable for which the regression coefficient went to zero for the LTPP dataset and STI for the MnROAD dataset. For both LTPP and MnROAD dataset, SCI was the last variable for which the regression coefficient became zero, and thus is the dominant predictor of the PCI prediction model.

4.4 VALIDATE PAVEMENT PERFORMANCE INDICATOR

The validation of the pavement performance indicator is performed using the Springdale, Ohio condition dataset. The road inventory and pavement condition data were provided by Highway Consulting Services, Inc. (HCS) of Scottsdale, Arizona. HCS provides pavement management services including a PMS software to the City of Springdale. There were 357 unique flexible pavement sections, and 1,284 pavement condition data entries were collected between June 21, 2013 and July 15, 2021 using the windshield survey method. For this analysis, pavements with the PCI greater than 64.9 with condition rating fair or better, appropriate for preventive and routine maintenance strategy were considered. The final pavement condition index was determined from 11 distress types collected which are categorized into four major condition indices: surface PCI, cracking PCI, support PCI, and structure PCI. The predominant indicator, cracking PCI was determined using the LASSO regression analysis method and the LASSO trace constructed is shown in Figure 4-1. A comparison between preservation treatments recommended by the Springdale PMS analysis and by SCI was performed to ensure SCI can be used as a performance measure in determining the treatment strategy. Using SCI, 92% of entries matched treatment recommended by the Springdale PMS analysis procedure while 8% recommended a different treatment. SCI recommended a heavier treatment on 75% of the analysis sections and a lighter treatment on 25% of them that did not match Springdale PMS analysis recommended treatments. Therefore, SCI can be used as a pavement performance indicator to determine pavement preservation needs reasonably and conservatively.

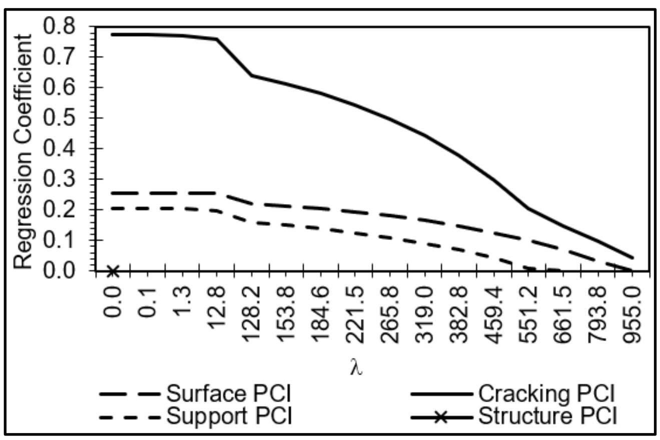


Figure 4-1: LASSO Trace for Springdale, Ohio Flexible Pavement Condition Data

4.5 PAVEMENT PERFORMANCE MODELS

The objectives of the pavement performance prediction models are to allow agencies to predict pavement condition in the future, to develop annual pavement maintenance programs meeting the budget, to compare the performance of different preservation treatments, and to evaluate the effectiveness of a specific preservation treatment. Since the intent of a preservation treatment is to extend the life of an existing pavement in a structurally sound condition, it is imperative to preserve the pavement before it declines rapidly to poor condition requiring a more costly rehabilitation treatment. This study presents and compares the performance of different flexible pavement preservation treatments using pavement condition performance curves developed from the LTPP dataset. Historical pavement condition, site condition, traffic condition, original construction data, and maintenance history were downloaded from the LTPP database and a rigorous combing of the data was performed. The manual data cleaning process involves removing sections that have only one survey data, incomplete or inconsistent distress data, improve in pavement condition without maintenance activity, decline in pavement condition unrealistically, or remain in the same pavement condition for several consecutive survey years. After data scrubbing, there were historical pavement condition data for 41 slurry seal treated sections, 27 chip seal sections, 27 hot-mix dense graded thin overlay sections, and 50 original hot-mix dense graded asphalt pavement sections remaining for use in developing PCI and SCI based pavement performance curves by treatment types.

Pavement condition deteriorates over time and the historical pavement condition data was used to develop pavement performance curves for different preservation treatments. To best fit the historical PCI and SCI data collected over time, the pavement performance is captured by the sigmoidal fitting function and shifting equation, initially developed by Sotil and Kaloush (2004) and revised as shown in the mathematical expression, Equation 4-3:

$$\text{PCI or SCI} = a + \frac{b}{\left(1+\exp^{(c*T+d)}\right)^{e}} \qquad \text{Equation 4-3}$$

where:

T = adjusted time (in years) since the last major construction or maintenance activity to best fit the sigmoidal function,

a = minimum PCI,

b = span of PCI, and

c,d,e = shape parameters of the sigmoidal function.

Since pavement deterioration rate is assumed to be similar for the same surface treatment pavement type, pavement performance curves for the original pavement with no subsequent preservation treatment, thin overlay, chip seal, and slurry seal treated pavement sections were developed. The criteria to minimize the total-error of predicted PCI versus observed PCI was achieved by changing shift factors and parameters of the sigmoidal function.

The service life extension (SLE) of an existing pavement following a specific preservation treatment application can be estimated as the time difference in year between treatment application date and when the treated pavement reaches the threshold PCI value of 70. The characteristics of each type of preservation treatment performance model and the accuracy of each model are presented in Table 4-2 and Table 4-3. As shown in Figure 4-2 and Figure 4-3, the original hot-mix dense graded asphalt pavement without any maintenance activities is expected to remain in the preservation treatment condition region for 8.1 years based on the PCI model or 8.0 years based on SCI model before it rapidly declines then tapering off and approaching PCI of 0. Applying thin hot-mix dense graded asphalt overlay to an existing pavement is anticipated to keep the pavement above PCI or SCI of 70 for an additional 9.2 years based on the PCI model and 9.7 years based on the SCI model respectively. An application of chip seal to an existing pavement is anticipated to keep the pavement to remain above PCI or SCI of 70 for an additional 7.2 years based on the PCI model and 7.2 years based on the SCI model. An application of slurry seal to an existing pavement is anticipated to keep the pavement to remain above PCI or SCI of 70 for an additional 4.2 years based on the PCI model and 4.2 years based on the SCI model.

The added 38 mm thick wearing course is expected to deteriorate at the slowest rate; even slower than the original hot-mix dense graded asphalt pavement. Slurry seal, on the other hand, deteriorates at a faster rate than the chip seal and thin overlay, which is rational. Comparing the standard error ratio for all 4 types of pavement surfaces using both PCI and SCI based models, the pavement performance model for the original pavement is the most accurate with S_e/S_y of 0.29 for PCI based model or 0.31 for SCI based model, respectively. The corresponding R^2 are 0.94 for PCI and SCI based performance models for the original pavement without any maintenance activities. The slurry seal pavement performance model is least accurate with S_e/S_y of 0.74 for the PCI based model or 0.74 for the SCI based model respectively. The corresponding R^2 are 0.74 for PCI and SCI based performance models for the slurry seal.

Table 4-2: Pavement Condition Index (PCI) Based Pavement Performance Model Parameters

Surface Type	Original Pavement	Thin Overlay	Chip Seal	Slurry Seal
n	148	74	78	118
p	50	27	27	41
a	0.00	0.00	0.00	0.00
b	98.47	99.05	94.23	96.43
c	0.87	0.37	0.86	2.38
d	-6.38	-3.49	-5.98	-5.55
e	0.31	0.54	0.36	0.07
S_e/S_y	0.29	0.42	0.47	0.63
R^2	0.94	0.88	0.85	0.74
SLE (yrs.)	-	9.2	7.2	4.2

Table 4-3: Surface Cracking Index (SCI) Based Pavement Performance Model Parameters

Surface Type	Original Pavement	Thin Overlay	Chip Seal	Slurry Seal
n	148	74	78	118
p	50	27	27	41
a	0.91	0.00	0.00	0.00
b	98.13	96.99	93.52	96.54
c	0.88	0.62	0.86	2.38
d	-6.18	-4.50	-5.86	-5.58
e	0.28	0.19	0.33	0.07
S_e/S_y	0.31	0.45	0.50	0.63
R^2	0.94	0.87	0.84	0.74
SLE (yrs.)	-	9.7	7.2	4.2

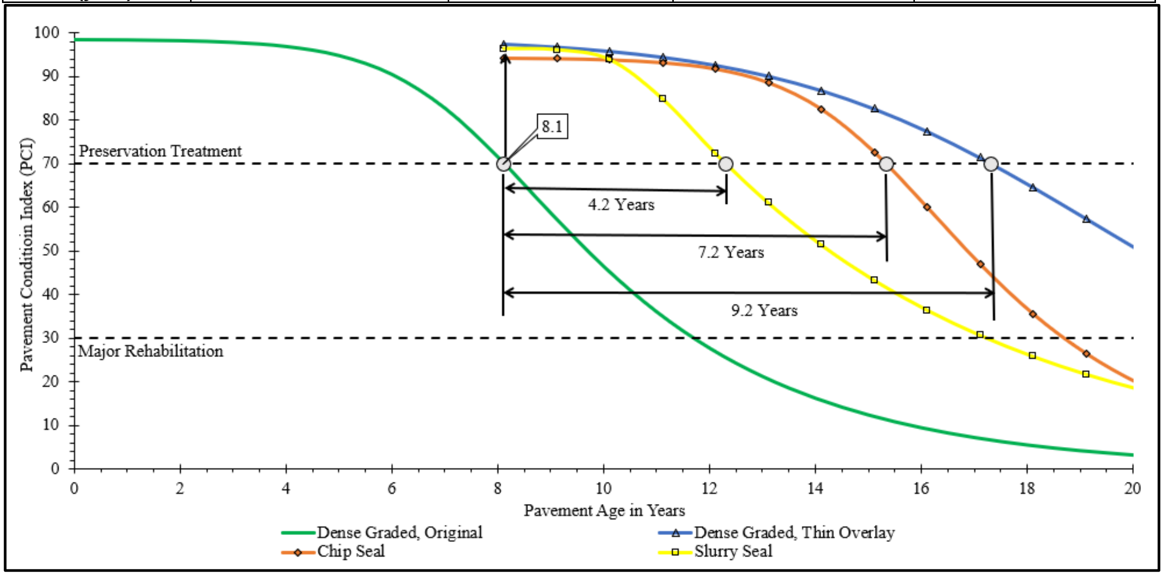


Figure 4-2: Pavement Condition Index (PCI) Based Pavement Performance Curves

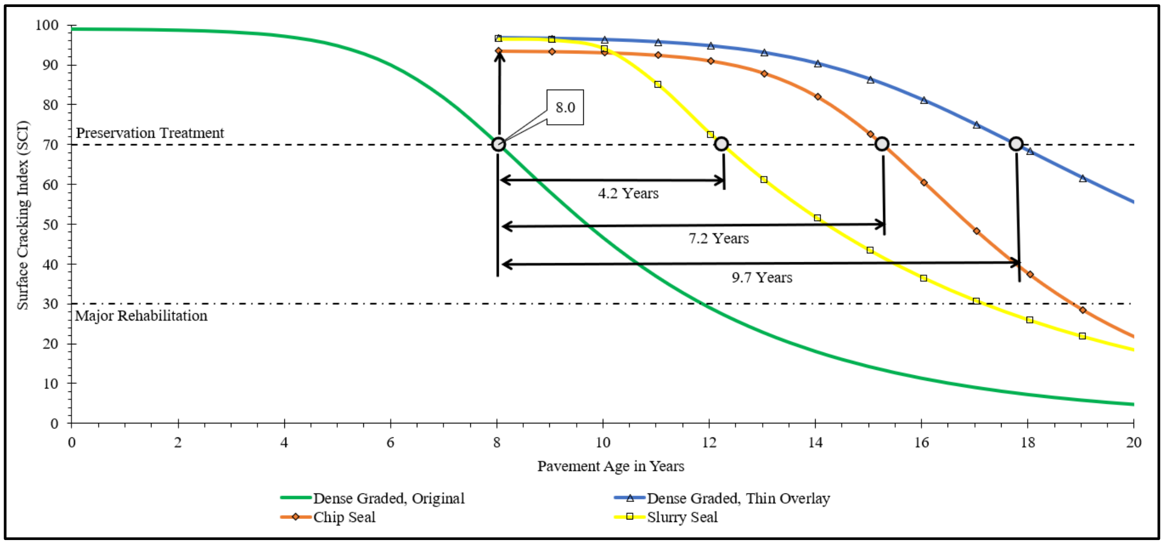


Figure 4-3: Surface Cracking Index (SCI) Based Pavement Performance Curves

Because the rate of pavement deterioration differs by the pavement surface type, the preservation treatment application timing needs to be planned accordingly. The rate of change of PCI (PCI') or the rate of change of SCI (SCI’) can be determined by taking the derivative of the sigmoidal function represented by Equation 4-4:

$$\mathrm{PCI'or\ SCI'} = -b * c\left(\exp^{c*T+d} + 1\right)^{-e-1}\exp^{c*T+d+1} \qquad \text{Equation 4-4}$$

The maximum PCI’ and SCI’ for the original pavement is expected to occur 8.7 years after construction at the PCI deterioration rate of 114 PCI/yr. and 8.5 years after construction at SCI deterioration rate of 119 SCI/yr. The maximum PCI’ and SCI’ for thin overlay pavement is expected to occur 11.2 years after construction at the PCI deterioration rate of 36 PCI/yr. and 9.9 years after construction at SCI deterioration rate of 98 SCI/yr. The maximum PCI’ and SCI’ for the chip seal section is expected to occur 8.1 years after construction at the PCI deterioration rate of 101 PCI/yr. and 8.1 years after construction at SCI deterioration rate of 104 SCI/yr. The maximum PCI’ and SCI’ for the slurry seal section is expected to occur 3.4 years after construction at the PCI deterioration rate of 478 PCI/yr. and 3.4 years after construction at SCI deterioration rate of 480 SCI/yr. Therefore, the pavement deterioration rate is greatest for slurry seals and lowest for thin overlay.

4.6 OPTIMAL TIMING FOR PRESERVATION TREATMENT APPLICATIONS

Rajagopal and George (1990) investigated the effect of timing and level of maintenance treatments on the overall pavement performance and concluded that the life cycles of treatments increase as the thickness of the overlay increases from 13 mm (0.5 in) of hot mix asphalt concrete (HMAC) surface treatment to 25 mm (1 in) thin HMAC overlay or 89 mm (3.5) thick HMAC overlay. Furthermore, the life cycles of all three maintenance treatments applied earlier in pavement's life while the pavement was in fair condition with pavement condition rating (PCR) of 70 was significantly greater compared to when timing was deferred to a deteriorated pavement with PCR of 50. Even a crack seal when applied too soon was found to add little benefit to the overlay, and when applied too late yielded minimal improvement since the overlay was already in an advanced stage of deterioration (Mousa, et al., 2019). There is an optimal age or condition where the cost effectiveness associated with a chosen treatment is maximized. The range of optimal age or condition is defined as the optimal timing to apply a treatment (Peshkin, Hoerner, & Zimmerman, 2004).

The relationship between the pretreatment pavement condition and the performance of the pavement after preservation treatment measured in terms of the SCI was investigated and the threshold SCI to apply the preservation treatment was determined. The lower limit SCI threshold to trigger a specific type of preservation treatment was determined using engineering judgment and by considering both the cost effectiveness analysis and the SLE relative to the expected SLE modeled by the treatment performance curves. There were 19 hot-mix dense graded thin overlay sections, 21 chip seal sections, and 12 slurry seal sections for which the pretreatment pavement condition data were available. Figure 4-4 through Figure 4-6 show pavement performance for these sections before and after preservation treatments. The cost-effectiveness analysis was performed on sections that had pretreatment condition data, SCI data for the duration of the expected SLE derived from the performance model for each specific treatment and SCI around 70. In cases when SCI data available did not reach SCI of 70, the sigmoidal function was fitted to the available data and the data were extrapolated to approximate SLE. The sections which received pretreatments including milling and crack sealing and atypical sections indicated by the dashed lines in Figure 4-4 through Figure 4-6 were removed from the cost effectiveness analysis. Due to the limitation on LTPP dataset's historical pavement condition data availability, 10 hot-mix dense graded thin overlay sections, 14 chip seal sections, and 8 slurry seal sections were available to perform cost-effectiveness analysis.

The unit costs for the installation of each preservation treatment obtained from the City of Phoenix were used to analyze the effect of the pretreatment condition on the cost effectiveness of a specific treatment. The cost effectiveness analysis is not intended to compare the cost-effectiveness between the treatments. The cost effectiveness index (CEI) was determined by a simple function taking the ratio of unit cost and the anticipated years of SLE and presented by Equation 4-5:

$$CEI = \frac{Unit\ Cost\ \left(\frac{\$}{m^2}\right)}{SLE\ (years)} \qquad \text{Equation 4-5}$$

A lower CEI scenario indicates a more cost-effective option. The costs for preservation treatments are dependent upon several factors, including the availability of material and contractors. The unit cost for the thin overlay was about \$12.00/m^2, \$7.50/m^2 for chip seal and \$2.75/m^2 for slurry seal in 2021. When pretreatment pavement condition is above the lower limit threshold, the life extension provided from a specific preservation treatment is greater while CEI is lower. Considering data shown in Table 4-4 and Figure 4-4 through Figure 4-6 and using engineering judgment, the thresholds for the cost-effective options can be established as greater than 70 SCI for thin overlay treatment, greater than 75 SCI for chip seal, and greater than 80 SCI for slurry seal treatment.

The lines with circle markers denote sections that received the preservation treatment at the optimal time. The lines with triangle markers denote sections that received the preservation treatment beyond the optimal time. The SCI before maintenance activity is represented by marker with solid fill while SCI after treatment is represented by marker with no fill. A treated section whose performance was better or worse than expected is represented by the dashed line, while a treated section performing as expected is represented by the solid line.

As shown in Figure 4-4, green dashed lines with circle markers represent SCI for the sections with pre-overlay SCI above the threshold values for an overlay treatment but performed slightly lower than expected. These sections were constructed on a treated base over the untreated clay subgrade with low strength and dusty soil condition and poor construction quality indicated by medium severity non-wheel path longitudinal cracks at the construction joints. The red dashed lines with triangle markers are field condition data for LTPP sections with pre-overlay SCI below the threshold values for an overlay treatment but performed better than expected. Their great performances are attributed to the treated subbase and base or the installation of nonwoven geotextile and at least 28 mm milled surface prior to the thin overlay.

The green dashed lines with circle markers shown in Figure 4-5 represent field condition data for the sections with pretreatment SCI above the chip seal treatment threshold values but yield lower than expected SLE. The chip seal treatment's poor performance can be attributed to the construction or the subgrade soil issue. The manual distress surveys reported the separation of construction joints, wearing of the chips exposing the construction joint or longitudinal cracking throughout the construction limit within 3 years after construction. The section of pavement constructed on pullman clay loam experienced the highest shrink-swell potential and lowest soil strength. The manual distress surveys reporting an increase from 1.2 m^2 of low severity fatigue cracking area to 21.7 m^2 medium severity fatigue cracking area within 2 years indicated the poor chip seal treatment performance can be attributed to the poor subgrade soil condition.

The green dashed lines with circle markers shown in Figure 4-6 represent field condition data for a section in Ontario, Canada and another in Kansas, USA which performed substantially lower than expected. Both sections were located in wet and freezing climatic regions. The manual distress survey for the section in Ontario reported that the slurry seal treatment was damaged by the snowplow. The section in Kansas was constructed on untreated lean inorganic clay subgrade with low strength and dusty soil conditions.

Table 4-4: Cost Effectiveness Analysis Results

Pretreatment SCI	SLE (yr.)	CEI ($/m^2/yr.)
Thin Overlay		
91	10.36	1.16
87	12.80	0.94
83	10.01	1.20
78	9.62	1.25
68	4.93	2.43
57	3.67	3.27
53	6.06	1.98
49	7.37	1.63
48	5.46	2.20
32	8.49	1.41
Chip Seal		
94	8.24	0.91
94	7.95	0.94
89	7.45	1.01
88	9.15	0.82
85	8.65	0.87
74	6.04	1.24
73	6.31	1.19
72	3.75	2.00
70	6.12	1.22
66	4.94	1.52
65	4.35	1.72
64	1.28	5.86
58	1.45	5.17
32	3.78	1.98
Slurry Seal		
88	8.38	0.33
68	2.96	0.93
58	2.54	1.08
56	3.76	0.73
53	1.76	1.56
47	3.92	0.70
40	3.34	0.82
13	3.38	0.81

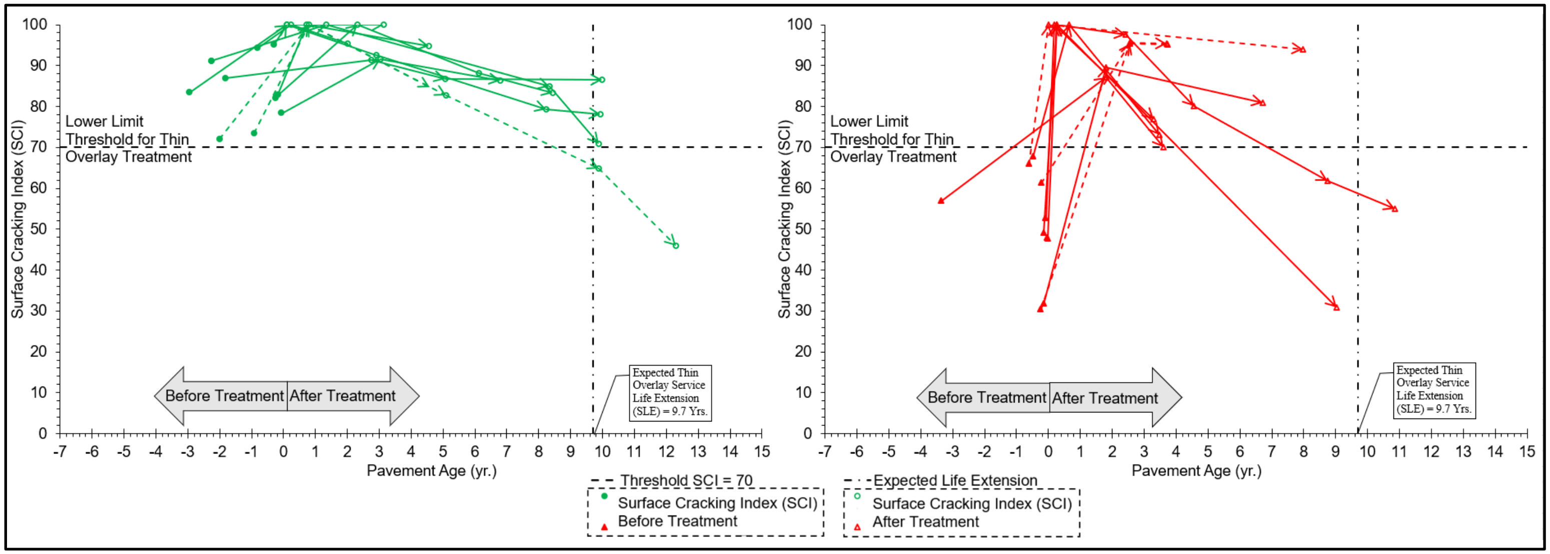


Figure 4-4: Thin Overlay Treatment Threshold

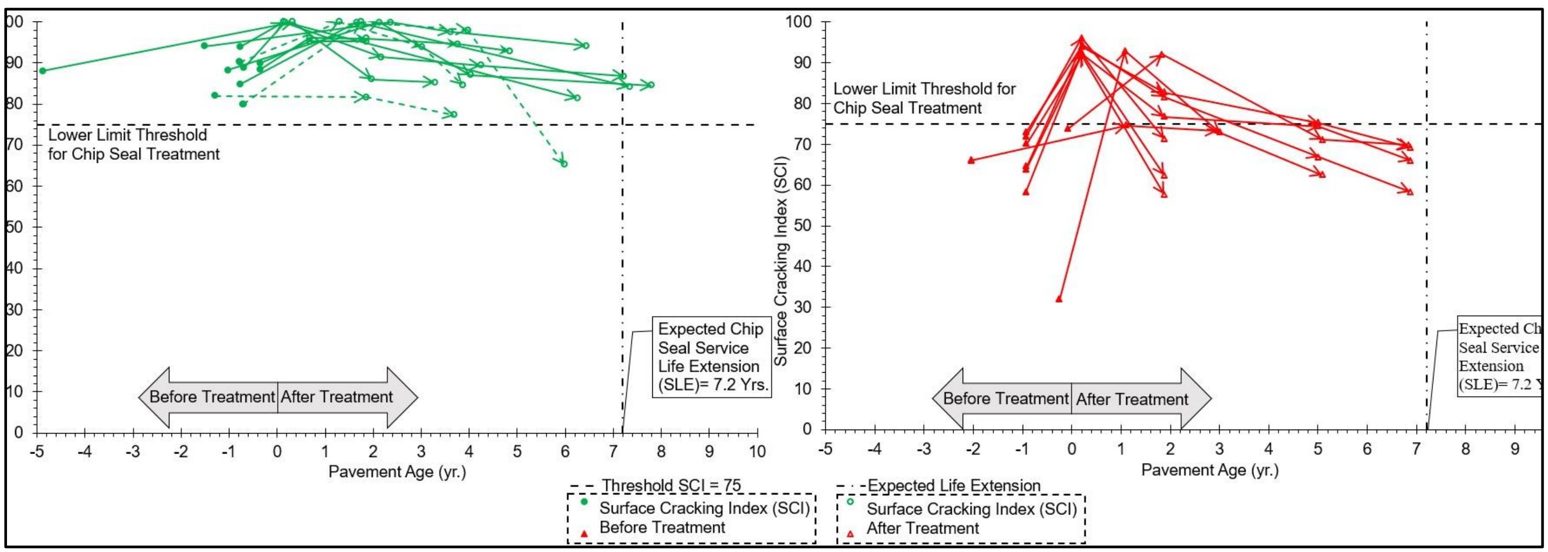


Figure 4-5: Chip Seal Treatment Threshold

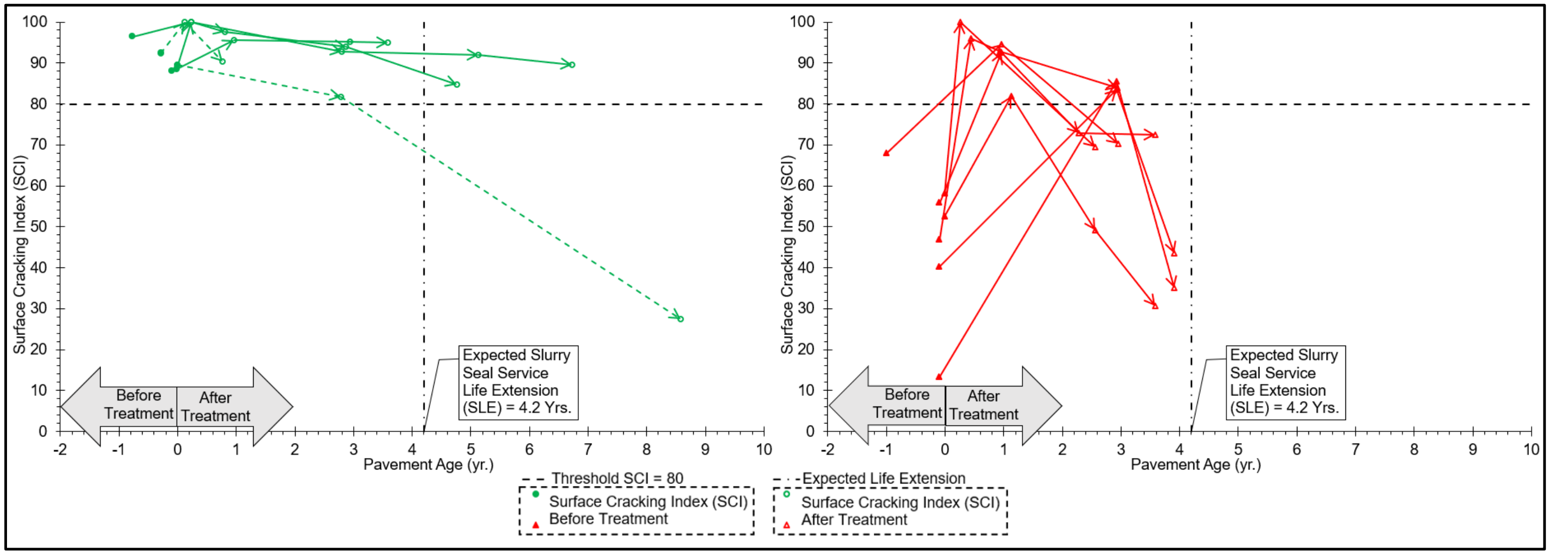


Figure 4-6: Slurry Seal Treatment Threshold

4.7 PRESERVATION TREATMENT DECISION TREE

Only pavements which have gone through at least a full year of temperature variations are recommended for preservation treatments. Based on a combination of past engineering experience, review of LTPP distress inspection videos and images, and analysis of pavement distress survey maps and data, the performance measure, surface cracking, was selected. This performance measure provides quantifiable benefits associated with preservation treatment applications and trackable pavement performance over time. Since preservation treatments do not add structural strength nor repair deep ruts or potholes but do correct surface cracking, monitoring pavement surface cracking is appropriate. Because the observed fatigue cracking on the existing pavement surface indicates pavement structural failure, the preservation treatment decision tree developed from analyzing the pavement surface cracking is supplemented with the fatigue cracking limit as shown on Figure 4-7.

A review of thin overlay, chip seal, and slurry seal projects located in the City of Phoenix which were completed between 2018 and 2021 were performed to detect the first visible pavement surface distress. The earliest appearance of reflective cracking was observed as little as 3 months after chip seal and slurry seal and slightly under ten months after thin overlay. Dhakal et al. (2016) and Nam et al. (2014) noted the reflection cracking propagation rate of 25 mm per year on hot-mix asphalt overlay. Common practices to prevent reflective crack initiation are milling to the crack depth and crack sealing. However, based on the field observations, on heavily fatigued cracking pavement sections, crack depth can be greater than 38 mm, which is the thickness of the thin overlay. Full depth patching as a pretreatment for preservation treatment is not cost effective for consideration for a large area. The sections with extremely high fatigue cracking areas with a lower SCI affecting the pavement structural capacity were removed before the fatigue cracking limits were established. The fatigue cracking limits were developed as the percent of fatigue cracking by severity for the corresponding optimum SCI range for the specific preservation treatment and reviewing distress images.

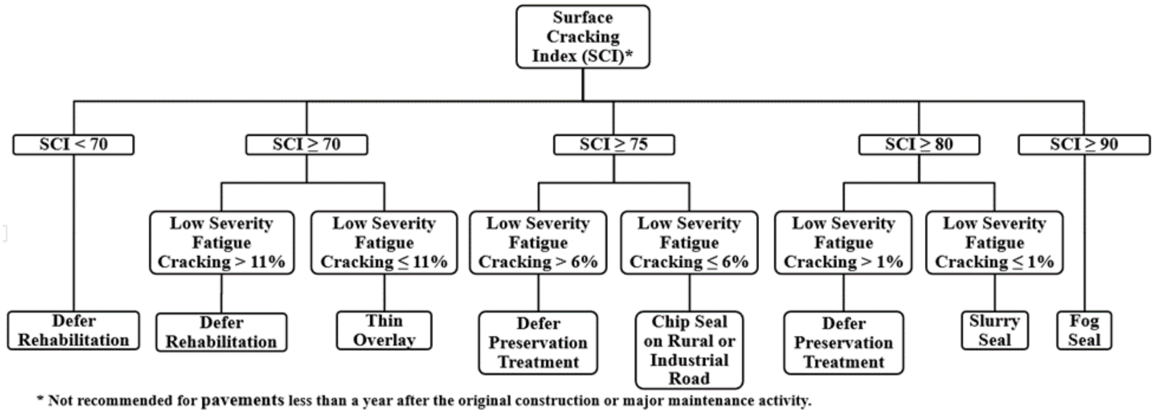


Figure 4-7: Preservation Treatment Selection Decision Tree

Pavements with SCI less than 70 or SCI greater than or equal to 70 exhibiting greater than 11% low severity fatigue cracks are considered far too deteriorated or cost effective for preservation treatments. Existing pavements with SCI greater than and equal to 70 exhibiting less than or equal to 11% low fatigue cracks are recommended for thin overlays. Rural or industrial roads between SCI greater than or equal to 75 exhibiting less than or equal to 6% low severity fatigue cracking are recommended for chip seals. If greater than 6% low severity fatigue cracking is observed on the rural or industrial roads, deferring treatment until pavement condition is warranted for thin overlay treatment is recommended. Pavements with SCI greater and equal to 80 exhibiting less than or equal to 1% low severity fatigue cracking are recommended for slurry seal while pavement with a higher fatigue cracking percentage is not recommended for preservation treatment until it is ready for chip seal or overlay treatments. A structurally sound pavement section with SCI greater than or equal to 90 that is older than a year and has gone through at least one summer heat is recommended for a fog seal or seal coat.

4.8 SUMMARY OF FINDINGS AND CONCLUSIONS

This first subsection of this portion of the study investigated pavement performance condition indicators and three performance measures including surface cracking, surface texture, and surface deformation to represent the overall pavement condition. The second subsection, pavement performance models, compared the ASTM method of pavement performance measure, PCI, to the proposed performance measure, surface cracking. The third subsection, optimal timing for preservation treatment applications, provided the lower bound on the surface cracking value to trigger a specific preservation treatment. The fourth subsection, preservation treatment decision tree, provided the triggers to select preservation treatments based on surface cracking.

The primary focus of a network level pavement preservation program is to apply the right preservation treatment on the right road at the right time and thereby keep the good roads in good condition for an extended period. A successful implementation of the pavement preservation program allows an agency to provide guidance in the selection and timing of the preservation treatment for its street network considering the budget, to objectively monitor the performance of a specific treatment over its lifetime, and to measure the cost-effectiveness of the preservation treatment. PMS relies on prediction of pavement performance models developed based on some historical information.

The major findings from this part of the research study are highlighted below:

1. Pavement surface cracking index SCI is strongly correlated to the pavement condition index for the PCI range above 70.
2. SCI can be used as a pavement performance indicator to perform PMS analysis for the preservation program.
3. Based on both the PCI and SCI performance curves developed in this study, the expected life extension, and the rate of deterioration for original hot-mix dense graded asphalt pavements with no maintenance, hot-mix dense graded thin overlay, chip seal, and slurry seal are different and overlay outperformed others.
4. Although performance of preservation treatment is affected by the pretreatment pavement condition, environment, traffic loading, and construction and material quality, due to the lack of sufficient data only the effect of the existing pavement condition prior to the treatment on the performance of the preservation treatments such as thin overlay, chip seal, and slurry seal were investigated. Based on the analysis, the low strength and expansive soil condition, snowplow activity, and deficient construction quality in wet regions were observed to cause preservation treatments to deteriorate at a faster pace

than expected. However, thin overlay treatment when applied on treated subbase, base, and milled pavement surface was observed to outperform others without pretreatments.

5. Based on the SCI analysis, a preservation treatment decision tree was developed to incorporate into the preservation treatment program and or pavement management systems. The threshold to trigger overlay treatment is when SCI is greater than 70 with a max low severity fatigue cracking limit of 11%; chip seal is when SCI is greater than 75 with a max low severity fatigue cracking limit of 6%; slurry seal is when SCI is greater than 80 with max low severity fatigue cracking limit of 1%; and fog seal is when SCI is greater than 90.

CHAPTER 5

VALIDATION OF CITY OF PHOENIX PAVEMENT CONDITION ASSESSMENT METHOD

5.1 INTRODUCTION

Pavement condition assessment methods range widely from manual survey to semi-automated to fully automated survey. Pavement condition data quality and the cost to collect and analyze the data also differ depending on the pavement condition assessment method. This chapter explores four types of pavement condition assessment methods currently available including Automated Road Analyzed (ARAN), ASTM manual survey, windshield survey, and RoadBotics survey methods as well as the simplified survey method proposed in the previous chapter. The objectives of this portion of the research work are: (1) to validate the compatibility of the ARAN van to perform a reliable and accurate pavement condition assessment and (2) to present other agencies with the different pavement assessment methods to assist in selecting the appropriate method in managing their street network.

In December 2019, RoadBotics assessed approximately 22.5 km (14 mi) of streets in the Phoenix downtown area. It encompasses two quarter sections (QS 11-27 and QS 11-28) and the area is bounded by Van Buren Street and Portland Street to 7th Avenue and 7th Street. There were 27 street sections evaluated and they consisted of six (6) arterial streets, six (6) collector streets, two (2) minor collector streets, and thirteen (13) residential streets. Figure 5-1 shows the map of the area assessed and color-coded to display different street classification. These 27 streets were driven with the ARAN van in June 2020 and analyzed using the City of Phoenix method to generate numerical pavement condition data. A windshield survey was performed in May 2020 and a manual field assessment was performed in December 2020. Since not all of the surveys were performed at the same time frame, the comparison of the pavement condition is relative.

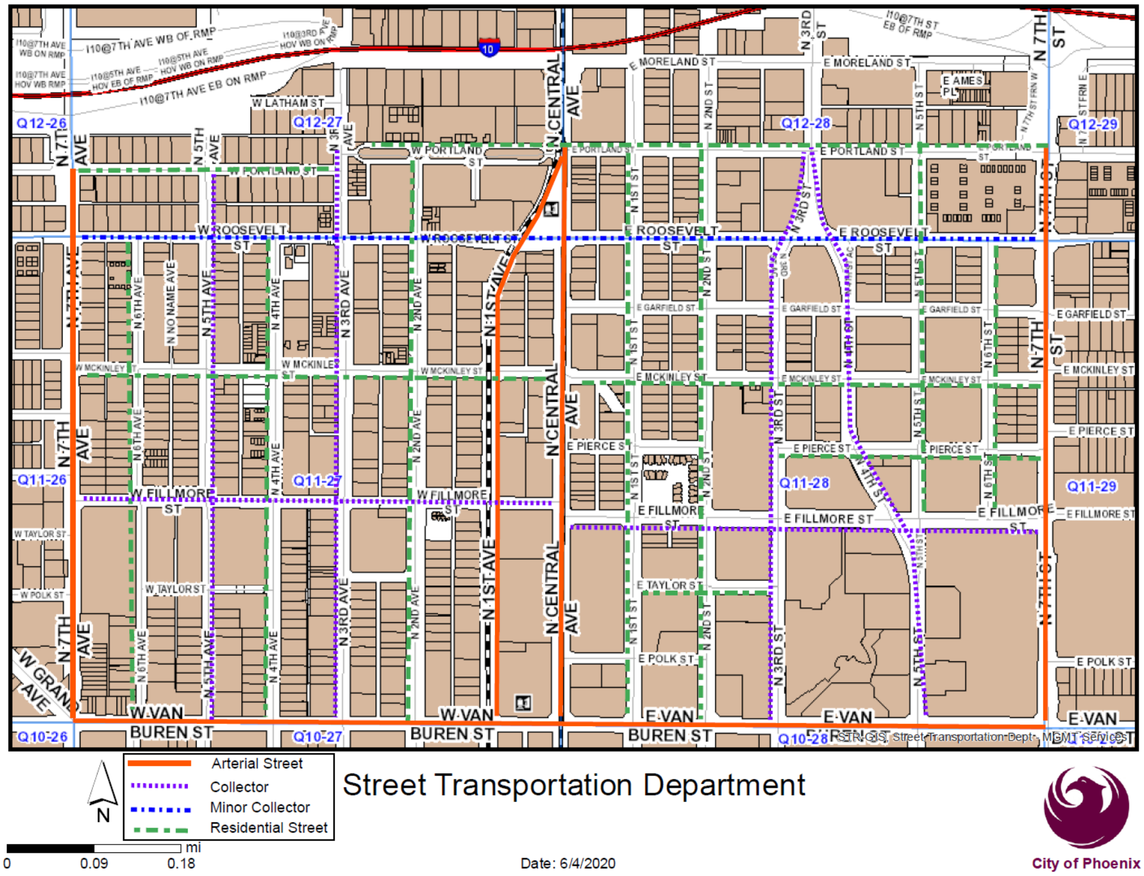


Figure 5-1: Pavement Condition Assessment Method Study Area Location Map

5.2 PAVEMENT CONDITION ASSESSMENT METHODS

5.2.1 Fugro Automated Road Analyzed Data Collection Method

ARAN van is equipped with laser and profiler to collect pavement condition data and Vision software is used to classify and rate pavement distresses such as fatigue crack, longitudinal wheel path crack, longitudinal non-wheel path crack, transverse crack, mean profile depth, rut depth, and IRI. The Vision output is reported with the severity and extent of each distress type analyzed. Vision report is then imported to dTIMS analysis software to generate pavement condition index and individual distress index ranging from 0 to 100 where 0 represents poor pavement condition and 100 represents excellent pavement condition. Table 5-1 shows individual distress index and PCI generated by dTIMS using pavement condition ARAN collected.

Table 5-1: ARAN Assessed Pavement Condition Data

Street Name	Fatigue Crack Index	Longitudinal Non-Wheel Path Crack Index	Longitudinal Wheel Path Crack Index	Transverse Crack Index	Roughness Index	PCI
E. Fillmore St	67	92	81	96	38	41
E. McKinley St	52	87	48	64	16	22
E. Pierce St	60	97	90	96	22	33
E. Portland St	29	93	73	80	16	22
E. Roosevelt St	60	98	89	94	41	47
E. Taylor St	69	90	68	91	34	40
E. Van Buren St	58	91	83	94	38	43
N. 1st Ave	79	96	82	94	40	49
N. 1st St	82	93	83	93	39	48
N. 2nd Ave	85	97	88	96	42	51
N. 2nd St	37	88	48	78	21	21
N. 3rd Ave	4	97	82	94	8	15
N. 3rd St	32	94	64	83	19	23
N. 4th Ave	93	100	93	99	57	65
N. 4th St	53	95	69	83	17	26
N. 5th Ave	66	90	67	83	38	39
N. 5th St	25	90	61	81	18	20
N. 6th Ave	89	100	96	99	40	52
N. 6th St	42	94	69	92	31	31
N. 7th Ave	92	97	80	94	81	78
N. 7th St	74	92	62	86	45	46
N. Central Ave	83	97	87	96	38	48
W. Fillmore St	60	97	78	91	27	36
W. McKinley St	78	99	95	97	28	41
W. Portland St	69	98	91	98	41	49
W. Roosevelt St	70	99	94	97	25	38
W. Van Buren St	61	96	76	92	23	33

5.2.2 ASTM Manual Survey Method

In accordance with Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys (ASTM D6433-20, 2020), a manual survey was performed. Field manual evaluation was performed on 77 pavement condition inventory sections and all 19 distress types were evaluated. Each pavement inventory section area was 225 m^2 (2500 ft^2). The PCI which considers all distresses is shown in Table 5-2.

5.2.3 Simplified Survey Method

The simplified survey method was conducted by performing a manual evaluation of the cracking type distresses only. The SCI shown in Table 5-2 was determined by considering only cracking distresses and using ASTM deduct values.

Table 5-2: ASTM Based Pavement Condition Data

Street Name	From	To	PCI	SCI
E. Fillmore St	Central Ave	1st St	19	61
E. Fillmore St	2nd St	3rd St	59	59
E. Fillmore St	5th St	6th St	72	86
E. McKinley St	Central Ave	1st St	13	65
E. McKinley St	2nd St	3rd St	24	72
E. McKinley St	5th St	6th St	85	87
E. Pierce St	3rd St	5th St	58	62
E. Pierce St	6th St	7th St	91	93
E. Portland St	1st St	2nd St	39	32
E. Portland St	3rd St	5th St	30	47
E. Portland St	5th St	7th St	36	56
E. Roosevelt St	1st St	2nd St	61	61
E. Roosevelt St	4th St	5th St	95	100
E. Roosevelt St	6th St	7th St	31	43
E. Taylor St	2nd St	3rd St	100	100
E. Van Buren St	1st St	2nd St	54	63
E. Van Buren St	1st St	Central Ave	61	63
E. Van Buren St	5th St	7th St	32	48
E. Van Buren St	5th St	3rd St	77	94
N. 1st Ave	Van Buren St	Fillmore St	96	100
N. 1st Ave	Fillmore St	McKinley St	69	69
N. 1st Ave	McKinley St	Roosevelt St	78	90
N. 1st St	Polk St	Taylor St	79	91
N. 1st St	Pierce St	McKinley St	63	100
N. 1st St	Moreland St	Van Buren St	100	100
N. 2nd Ave	Van Buren St	Fillmore St	72	100
N. 2nd Ave	Fillmore St	McKinley St	90	90
N. 2nd Ave	McKinley St	Roosevelt St	89	89
N. 2nd St	Polk St	Taylor St	72	77
N. 2nd St	Pierce St	McKinley St	34	47
N. 2nd St	Garfield St	Roosevelt St	43	61
N. 3rd Ave	Van Buren St	Fillmore St	27	29
N. 3rd Ave	Fillmore St	McKinley St	19	22
N. 3rd Ave	Roosevelt St	Portland St	56	83

Table 5-3: ASTM Based Pavement Condition Data Cont'd

Street Name	From	To	PCI	SCI
N. 3rd St	Taylor St	Van Buren St	37	18
N. 3rd St	Fillmore St	Pierce St	1	45
N. 3rd St	Roosevelt St	Garfield St	79	90
N. 4th Ave	Van Buren St	Fillmore St	80	77
N. 4th Ave	Fillmore St	McKinley St	88	88
N. 4th Ave	McKinley St	Roosevelt St	91	91
N. 4th St	Pierce St	McKinley St	75	78
N. 4th St	McKinley St	Garfield St	77	77
N. 5th Ave	Van Buren St	Fillmore St	100	100
N. 5th Ave	Fillmore St	McKinley St	100	100
N. 5th Ave	Portland St	Roosevelt St	75	72
N. 5th St	Van Buren St	Fillmore St	38	69
N. 5th St	Fillmore St	Pierce St	36	61
N. 5th St	Roosevelt St	Portland St	57	56
N. 6th Ave	Van Buren St	Fillmore St	97	97
N. 6th Ave	Fillmore St	McKinley St	98	98
N. 6th Ave	McKinley St	Roosevelt St	95	96
N. 6th St	Pierce St	McKinley St	37	56
N. 6th St	Garfield St	Roosevelt St	38	57
N. 7th Ave	Roosevelt St	McKinley St	87	87
N. 7th Ave	McKinley St	Fillmore St	89	89
N. 7th Ave	Fillmore St	Van Buren St	90	91
N. 7th St	Polk St	Fillmore St	27	54
N. 7th St	Fillmore St	Pierce St	76	80
N. 7th St	Garfield St	Roosevelt St	79	80
N. Central Ave	Polk St	Fillmore St	61	100
N. Central Ave	Pierce St	McKinley St	27	63
N. Central Ave	Garfield St	Roosevelt St	80	97
W. Fillmore St	6th Ave	5th Ave	77	97
W. Fillmore St	4th Ave	3rd Ave	61	100
W. Fillmore St	2nd Ave	1st Ave	84	88
W. McKinley St	7th Ave	6th Ave	95	95
W. McKinley St	5th Ave	4th Ave	79	86
W. McKinley St	2nd Ave	1st Ave	78	74
W. Portland St	7th Ave	5th Ave	72	72
W. Portland St	5th Ave	3rd Ave	77	72
W. Portland St	2nd Ave	1st Dr	100	100
W. Roosevelt St	6th Ave	5th Ave	98	98
W. Roosevelt St	4th Ave	3rd Ave	96	96
W. Roosevelt St	2nd Ave	1st Ave	95	97
W. Van Buren St	6th Ave	5th Ave	35	54
W. Van Buren St	4th Ave	3rd Ave	36	23
W. Van Buren St	2nd Ave	1st Ave	52	53

5.2.4 RoadBotics Data Collection Method

RoadBotics uses smartphones mounted on the vehicle windshield to collect pavement images and artificial intelligence (A.I.) to identify individual distresses for pavement management. The application of machine learning to automate detection of distresses in pavement images captured by smartphones is achieved by training machines to recognize patterns. The RoadBotics A.I. is trained to look for pavement distresses such as potholes, patches/sealant, fatigue crack, pavement distortion, transverse/longitudinal crack, and surface deterioration. Each distress category and the overall condition is assessed at every 3 m (10 ft) interval in the direction of travel accurately, consistently, and objectively. With the machine learning application pavement distresses are detected, and the type and extent of the distresses are characterized from the pavement images, but the severity of distresses is not evaluated. The extent of potholes and patches/sealant are recorded as the number of potholes and patches/sealants. The extent of fatigue crack, pavement distortion, transverse/longitudinal crack, and surface deterioration are quantified as a percent of distress observed within the assessed section of the pavement. Based on the extent of these six pavement distresses combined, scores are calculated ranging from one (1) to five (5). Pavement with no or minor surface distress is rated and assigned a score of one (1), minor or surface damage with no critical issues is assigned a score of two (2), appearance of pervasive surface distresses is assigned a score of three (3), significant damage or emerging critical failures is assigned a score of four (4) and a major surface damage and/or critical fatigue issues is assigned a score of five (5). Its proprietary interactive platform is then used to analyze and map pavement quality. RoadBotics also has the option to score pavement sections by the high-definition pavement condition index (HD-PCI). Table 5-3 presents pavement condition data of 26 street evaluation sections based on RoadBotics assessment method. RoadBotics' simplified and automated approach in assessing pavement condition empowers agencies to make data-driven objective pavement management decisions about their street network and maintenance prioritization strategy.

Table 5-4: RoadBotics Assessed Pavement Condition Data

Street Name	Score	HD-PCI	Potholes	Fatigue Cracking (%)	Distortion (%)	Deterioration (%)	Patch/Seal	Transverse/ Longitudinal Cracking (%)
E. Fillmore St	1.38	88	3	1	1	23	205	78
E. Garfield St	3.07	62	0	49	0	70	166	93
E. McKinley St	2.66	69	4	42	0	52	137	92
E. Pierce St	1.08	93	0	0	0	21	16	28
E. Portland St	2.97	56	3	56	7	79	160	82
E. Roosevelt St	1.47	90	0	1	0	24	75	68
E. Taylor St	2.19	80	0	1	0	17	69	86
E. Van Buren St	2.00	80	0	0	0	51	205	92
N. 1st Ave	2.01	78	0	0	0	58	279	82
N. 1st St	1.76	84	1	0	0	34	48	67
N. 2nd Ave	1.31	85	0	0	0	24	79	76
N. 2nd St	2.88	61	1	32	0	57	213	99
N. 3rd Ave	3.80	44	6	73	0	86	186	91
N. 3rd St	2.65	66	4	13	0	74	255	98
N. 4th Ave	1.22	81	0	0	0	10	45	38
N. 4th St	2.22	75	6	26	0	52	122	70
N. 5th Ave	2.26	75	0	3	0	75	106	99
N. 5th St	3.05	58	1	48	0	83	218	94
N. 6th Ave	1.29	86	0	0	0	9	66	53
N. 6th St	2.95	62	0	68	0	65	79	92
N. 7th Ave	2.05	82	0	0	0	25	93	100
N. 7th St	2.32	78	0	1	0	31	322	73
N. Central Ave	1.68	85	0	0	0	41	345	41
W. Fillmore St	1.40	89	0	0	0	12	120	74
W. McKinley St	1.29	92	0	1	0	5	44	43
W. Portland St	1.48	88	0	0	0	10	80	61
W. Roosevelt St	1.15	92	1	1	0	39	71	44
W. Van Buren St	2.09	80	0	0	0	60	246	75

5.2.5 Windshield Survey Method

A manual windshield survey method involves a rater driving the road a few times and subjectively assessing the pavement condition in the field to gather the type, severity, and extent of pavement distresses observed. The overall rideability of the road and the maintenance rating is also assessed. There were twelve distresses considered and can be categorized into three main distress groups: surface, cracking, and support. The surface group consisted of distresses such as weathering/raveling, bleeding, patching and utility cut patching, potholes, and crack seal deficiency. Fatigue crack, transverse crack, longitudinal crack, block crack, and edge/random crack fall under cracking groups while rutting, settlement, and corrugations are grouped under the support distress category. Each type, severity, and extent of distress is assigned a deduct value as shown in Table 5-4. PCI ranges from 100 to 0, and based on the distresses observed, all the deduct values are summed and subtracted from 100 to determine PCI of the pavement. Table 5-5 provides the windshield survey findings based on only the distresses observed and pavement condition index.

Table 5-5: Deduct Points by Distress Type, Severity, and Extent

Distress Type		Severity	% Area			
			1-5	6-25	26-50	51-100
Surface	Weathering/Raveling	Low	0.5	1	1.75	2.5
		Medium	2.5	5	8.75	12.5
		High	5	10	17.5	25
	Bleeding	Low	2.25	3.75	6	7.5
		Medium	3.6	6	9.6	12
		High	4.5	7.5	12	15
	Patching and Utility Cut Patching	Low	0.9	1.5	2.4	3
		Medium	2.25	3.75	6	7.5
		High	4.5	7.5	12	15
	Potholes	Low	1.2	2.4	4.2	6
		Medium	3.6	7.2	12.6	18
		High	6	12	21	30
	Crack Seal Deficiency	Low	2.25	3.75	6	7.5
		Medium	3.6	6	9.6	12
		High	4.5	7.5	12	15
Cracking	Fatigue Cracking	Low	3.6	6	9.6	12
		Medium	6.3	10.5	16.8	21
		High	9	15	24	30
	Transverse Cracking	Low	3	5	8	10
		Medium	5.25	8.75	14	17.5
		High	7.5	12.5	20	25
	Longitudinal Cracking	Low	2.4	4	6.4	8
		Medium	4.2	7	11.2	14
		High	6	10	16	20
	Block Cracking	Low	1.8	2.7	3.6	4.5
		Medium	3.6	5.4	7.2	9
		High	6	9	12	15
	Edge or Random Cracking	Low	1.2	2	3.2	4
		Medium	2.1	3.5	5.6	7
		High	3	5	8	10
Support	Rutting	Low	2.7	5.4	7.2	9
		Medium	8.1	16.2	21.6	27
		High	12.5	27	36	45
	Settlement	Low	4.8	9.6	12.8	16
		Medium	8.4	16.8	22.4	28
		High	12	24	32	40
	Corrugation	Low	0.9	1.8	3.2	4.5
		Medium	1.8	3.6	6.3	9
		High	3	6	10.5	15

Table 5-6: Windshield Survey Pavement Condition Data

Street Name	Weathering - Severity	Weathering - Extent	Patch Deterioration - Severity	Patch Deterioration - Extent	Crack Seal Deficiency - Severity	Crack Seal Deficiency - Extent	Fatigue Cracking - Severity	Fatigue Cracking - Extent	Transverse Cracking - Severity	Transverse Cracking - Extent	Longitudinal Cracking - Severity	Longitudinal Cracking - Extent	Block Cracking - Severity	Block Cracking - Extent	Edge Cracking - Severity	Edge Cracking - Extent	PCI
E. Fillmore St							Medium	25					Low	25			87
E. McKinley St	Medium	100	Medium	50									Medium	100			73
E. Pierce St	Low	5															100
E. Portland St	Medium	100											High	100			73
E. Roosevelt St													Low	5		25	98
E. Taylor St	Medium	100							Low	25			High	100			68
E. Van Buren St													Low	100			96
N. 1st Ave	Medium	5							Medium	5	Low	5					90
N. 1st St	Medium	50	Low	25					Low	25	Low	25	Low	100			76
N. 2nd Ave									Low	25	Low	25					91
N. 2nd St	Medium	100	Medium	50			Low	5					Medium	100			69
N. 3rd Ave	Medium	100					Medium	50					High	100			56
N. 3rd St	Medium	100	Medium	50	Low	50	Low	25					Medium	100			61
N. 4th Ave													Low	50	Low	50	93
N. 4th St	High	25					Medium	5					Medium	50			77
N. 5th Ave	Medium	100							Medium	25	Medium	100					65
N. 5th St	Medium	100	Medium	50			Low	25					High	100			61
N. 6th Ave													Low	50			96
N. 6th St	Medium	25	Low	50			Low	25					Medium	100			78
N. 7th Ave									Medium	25	Medium	25					84
N. 7th St							Low	5	Medium	25	Medium	5	Medium	50			76
N. Central Ave			Low	5	Low	25			Low	25	Low	5					88
W. Fillmore St									Low	25	Low	25					91
W. McKinley St													Low	100	Low	50	92
W. Portland St									Low	50							92
W. Roosevelt St																	100
W. Van Buren St			Medium	25													96

5.3 A COMPARISON OF PAVEMENT CONDITION DATA

Since the arrival of the new ARAN 9000, the performance of the pavement condition assessment system has not been evaluated. The pavement condition index determined using the City of Phoenix method is compared to ASTM manual survey, windshield survey, and RoadBotics survey methods. The City of Phoenix PCI is also compared to SCI. The surveys were done at different times and the effort required to collect the data differs between the various methods. Table 5-6 shows the effort required to collect the condition data for 27 street sections considered for this portion of the research study. The Phoenix survey method requires the least field data collection effort, and the manual survey is the most labor intensive. Figure 5-2 shows Phoenix PCI is much lower than manual survey PCI, windshield survey PCI, RoadBotics HD-PCI and SCI. The difference in PCI between Phoenix PCI and others is increased when at a low PCI rating than at a higher PCI rating. The difference in PCI is lowest when the Phoenix PCI is 78.

Figure 5-3 shows the relationships between Phoenix PCI and condition data obtained from the manual survey (both PCI and SCI), windshield survey, and RoadBotics methods are weak and exhibit positive correlation. The weak correlation can be attributed to several factors. The change in pavement condition is due to aging and the change in pavement deterioration rate due to heavy duty construction activities. Since the manual surveys were performed for the 225 m^2 (2500 ft^2) pavement condition inventory sections rather than the whole road section, the condition data were not comparable.

Table 5-7: Required Field Effort for Condition Assessment

	ASTM Manual Survey Method	Phoenix Survey Method	RoadBotics Survey Method	Windshield Survey Method
Pavement Condition Assessment Date	12/28/20 – 1/5/21	6/25/20 – 6/26/20	12/7/19 – 12/10/19	5/18/20 – 5/31/20
No. of Collection Days	6 Days	2 Half Days	3 Days	5 Days
No. of Raters	2 Persons	2 Persons	1 Person	2 Persons

A field review of the pavement condition and treatment recommendation was performed in May 2020. Table 5-7 provides treatments recommended for 27 inventory sections along with the pavement condition data from ARAN, RoadBotics, and manual survey assessment methods. The field treatment recommendations are based on engineering judgment and consider the overall pavement section condition, maintenance history, and future construction activities. For example, E. Fillmore St, which received a micro seal about 30 months ago, would not be programmed to receive another preservation treatment to treat reflective cracking even when conditions warrant a preservation treatment. As shown in Figure 5-4, reflective cracking is the major pavement distress on the recently micro sealed pavement surface. An evaluation of the condition without consideration of the previous treatment would have warranted a heavier preservation treatment. Since the reflective cracking was not that visible during the windshield survey; the windshield survey PCI is more than twice the Phoenix PCI. However, The PCI for E. Fillmore St is low because of the low roughness index and does not reflect the field condition.

Based on the manual survey, the PCI on E. McKinley St between Central Ave and 1st St is 13, between 2nd St and 3rd St is 24, and between 5th St and 6th St is 85. The PCI difference between Phoenix PCI method and manual survey method is apparent especially on the pavement section exhibiting a vastly different condition within the section. The Phoenix PCI method scanned the whole length of the pavement section while the manual survey was performed for just a sample inventory area. In urban areas, such conditions are not impossible and making the pavement condition rating more complex. During the field review, slurry seal was recommended even though PCI represents pavement in poor condition. This is because the field treatment recommendation is based on the overall condition of E. McKinley St between Central Ave and 7th St as well as the anticipated improvements to the existing road after the developer completes the construction on E. McKinley St as shown in Figure 5-5.

Table 5-8: Field Assessed Treatment Recommendations and Pavement Condition Data

Street Name	Phoenix PCI	ASTM PCI	SCI	Windshield PCI	RoadBotics HD-PCI	Last Treatment	Treatment Date	Field Review Treatment Recommendation
E. Fillmore St	41	50	69	87	88	Micro Seal	12/14/2017	Do nothing
N. 6th Ave	52	97	97	96	86	Thin Overlay	2/4/2019	Do nothing
W. Roosevelt St	38	96	97	100	92	Thin Overlay	11/25/2019	Do nothing
W. Van Buren St	33	41	43	96	80	Fog Seal	2/1/2018	Do nothing
E. Van Buren St	43	56	67	96	80	Fog Seal	2/1/2018	Fog Seal
N. 1st Ave	49	81	86	90	78	Fog Seal	5/20/2018	Fog Seal
W. Portland St	49	83	81	92	88	Thin Overlay	7/18/2018	Fog Seal
E. Pierce St	33	75	77	100	93	Thin Overlay	2003	Fog Seal
E. Roosevelt St	47	62	68	98	90	New Pavement	4/26/2016	Fog Seal
N. 2nd Ave	51	83	93	91	85	Thin Overlay	2/4/2019	Fog Seal
N. 4th Ave	65	87	85	93	81	Thin Overlay	2/4/2019	Fog Seal
N. 7th Ave	78	89	89	84	82	Thin Overlay	10/21/2017	Fog Seal
N. Central Ave	48	56	87	88	85	Fog Seal	5/20/2018	Fog Seal
W. Fillmore St	36	74	95	91	89	Thin Overlay	2/4/2019	Fog Seal
W. McKinley St	41	84	85	92	92	Thin Overlay	2/4/2019	Fog Seal
N. 7th St	46	60	71	76	78	Micro Seal	2000	Slurry Seal
E. McKinley St	22	41	75	73	69	Thin Overlay	2003	Slurry Seal
E. Portland St	22	35	45	73	56	Thin Overlay	1/8/1991	Slurry Seal
E. Taylor St	40	100	100	68	80			Slurry Seal
N. 1st St	48	81	96	76	84	Thin Overlay	2003	Slurry Seal
N. 4th St	26	76	78	77	75	New Pavement	4/26/2016	Slurry Seal
N. 5th St	20	44	62	61	58	New Pavement	4/26/2016	Slurry Seal
N. 2nd St	21	49	62	69	61	Thin Overlay	8/26/2003	Slurry Seal
N. 5th Ave	39	92	91	65	75	Thin Overlay	6/30/2014	Slurry Seal
N. 3rd Ave	15	34	45	56	44	Micro Seal	5/20/1999	Overlay
N. 3rd St	23	39	56	61	66	Thin Overlay	1/12/1992	Overlay
N. 6th St	31	38	57	78	62	Thin Overlay	2003	Overlay

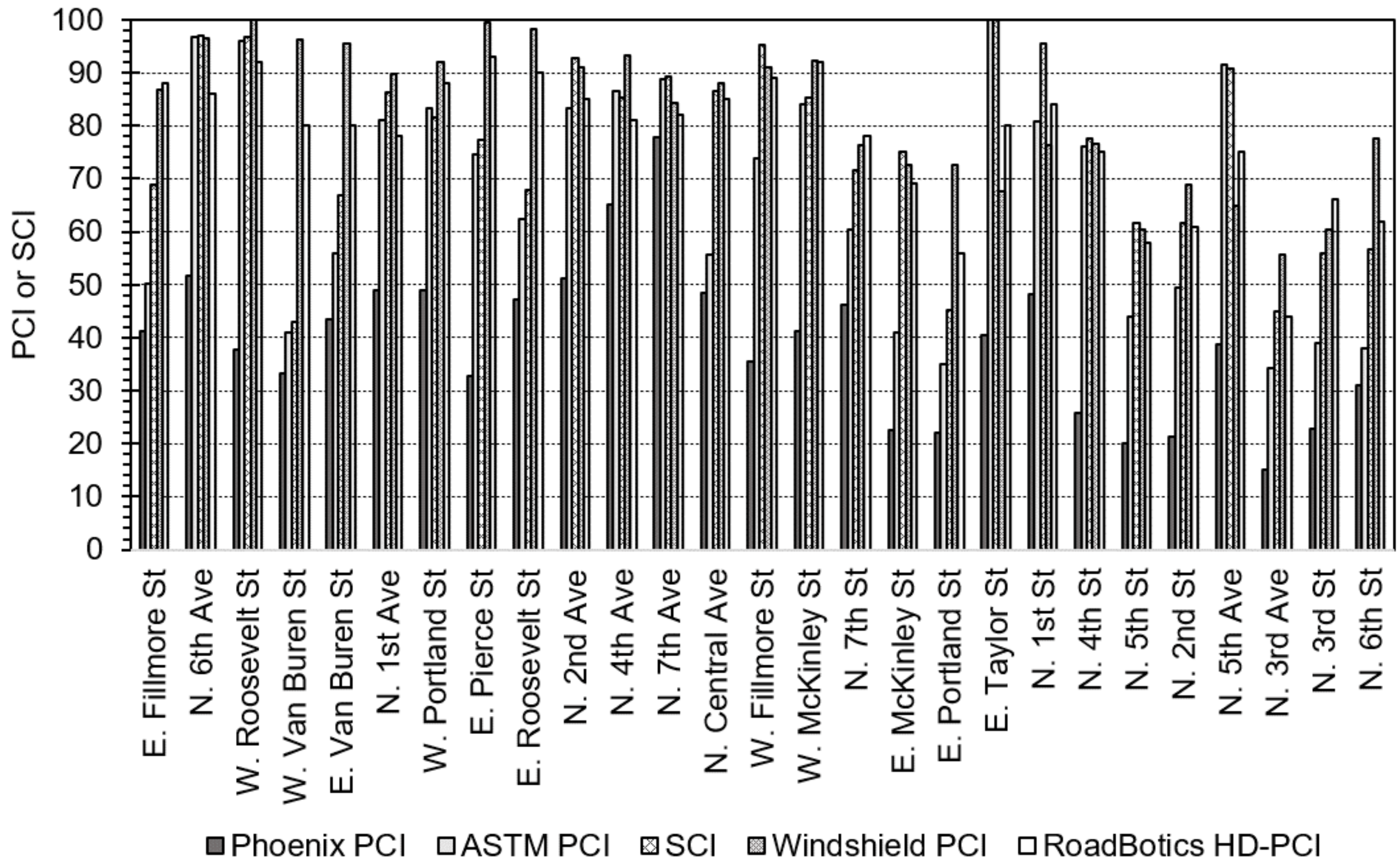


Figure 5-2: Pavement Condition Assessment Data Comparison

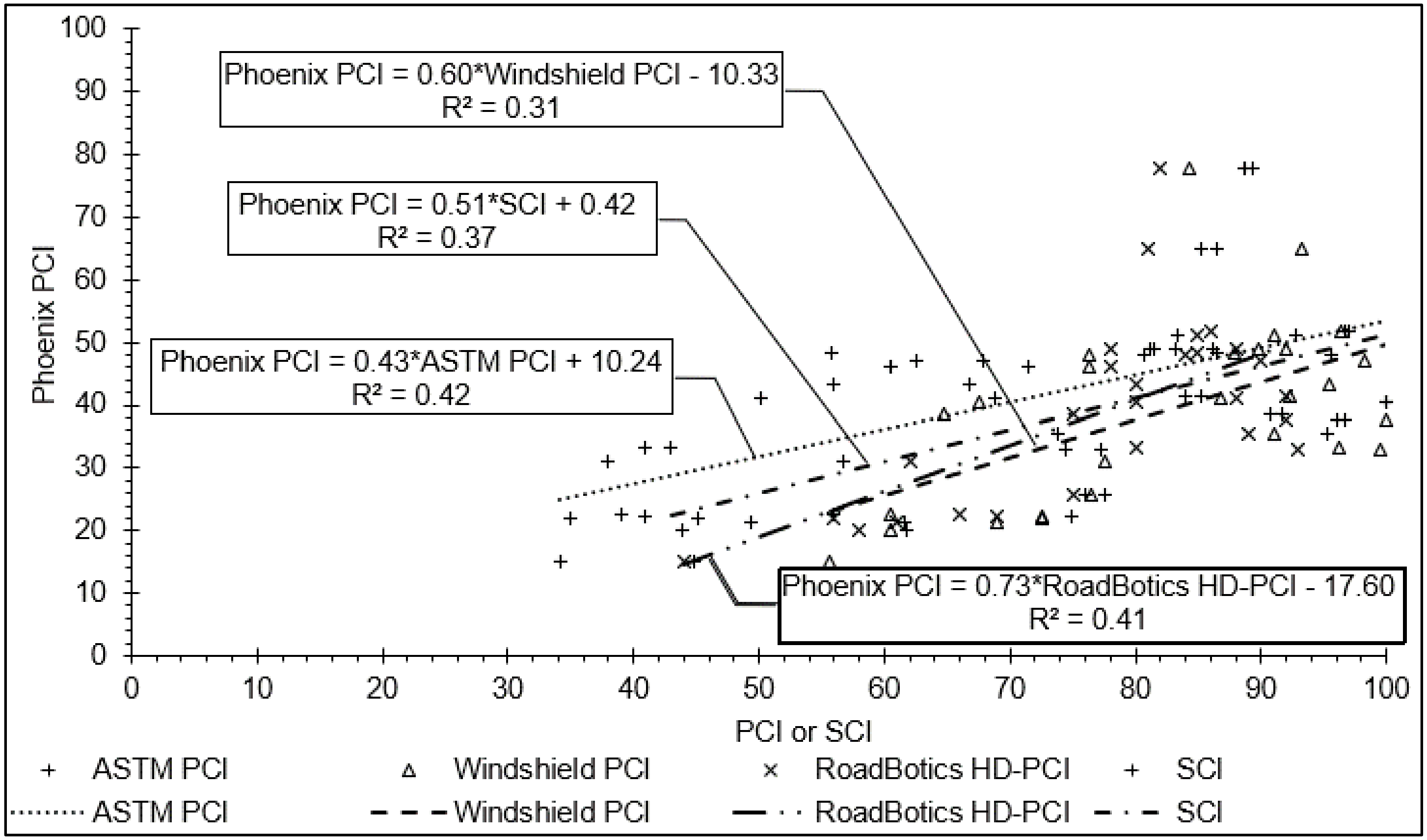


Figure 5-3: A Comparison of Phoenix PCI to ASTM Based PCI and SCI, Windshield Survey PCI, and RoadBotics HD-PCI

Figure 5-4: E. Fillmore St between 5th St and 6th St

Figure 5-5: E. McKinley St between 2nd St and 3rd St

5.4 SUMMARY OF FINDINGS AND CONCLUSIONS

This portion of the study validated the City of Phoenix's pavement condition assessment method using ARAN and presented other survey methods available. The major findings from this part of the research study are highlighted below:

1. The difference in the survey procedures, automated versus manual survey methods or surveying multiple sample survey inventory areas versus the whole length of the section, can result in a large difference in PCI.
2. The City of Phoenix PCI is much lower than PCI determined using RoadBotics and PCI or SCI determined from manual survey methods.
3. The City of Phoenix method of pavement condition assessment is weakly correlated with manual survey pavement assessment methods as well as the RoadBotics method.
4. Since the actual field treatment recommendation considers factors such as maintenance history and future construction activities, beyond the pavement condition, the PMS analysis can only be used as a tool to assist, not make the final decision, in recommending the specific preservation treatment.

CHAPTER 6

ESTABLISHING MACROTEXTURE INDEX

6.1 INTRODUCTION

This portion of the study is limited in scope to macrotexture with its wavelength ranging from 0.5 mm to 50.0 mm and is motivated by raveling observed on young pavements in the City of Phoenix and improper assessment of new chip seals as raveling. Based on a review of 10% of 7,800 km of Phoenix's flexible pavement street network, approximately 37% had a rougher pavement surface texture than slurry seal and approximately 3% had a rougher pavement surface texture than chip seal. The use of surface macrotexture to assess and monitor asphalt concrete pavements surface texture roughness and deficiencies such as bleeding and raveling is proposed. Bleeding caused by excessive binder content and low voids results in a partial or complete immersion of the aggregate into the bituminous binder. Raveling is the disintegration of a pavement surface by loss of binder and both fine and coarse aggregates. Raveling results from the separation of the bituminous film from the aggregates due to water, chemical, and mechanical actions, or poor material or construction qualities. Unless severely raveled and deeply pitted, raveling may not affect the pavement structure but both raveling and bleeding can have a substantial effect on the ride quality and safety.

Although numerous studies had been conducted to gain a better understanding of surface macrotexture, none had explored its long-term performance nor its applications to preservation treatment recommendation strategies. Therefore, the objectives of this study are: (1) to evaluate surface macrotexture performance over time and (2) to develop a pavement preservation treatment recommendation strategy to mitigate surface texture deficiencies.

6.2 RESEARCH METHODOLOGY

The research methodology encompasses the following:

1. Analyze the historical pavement condition, site condition, traffic condition, and original construction and subsequent maintenance history data.
2. Perform a rigorous data scrubbing to remove incomplete, erroneous, inaccurate, or unusual pavement macrotexture data.

3. Field investigates surface macrotexture for different types of flexible pavement surfaces using Automated Road Analyzer (ARAN) and volumetric method in accordance with ASTM specification E965 using glass sphere to establish the relationship between automated and manual survey methods.
4. Develop pavement surface macrotexture indicator, mean profile depth (MPD), based performance models for thin hot-mix dense graded asphalt overlay and chip seal.
5. Establish an optimal timing for the preservation treatment.
6. Develop a decision tree for preservation treatment selection.

6.3 PAVEMENT SURFACE MACROTEXTURE CHARACTERISTICS

The commonly used indicators for pavement surface macrotexture are macrotexture depth (MTD) and mean profile depth (MPD). The classic three-dimensional measure of pavement macrotexture is a volumetric method that can be performed in the laboratory and in the field. In this study, the volumetric method was used as a referenced macrotexture measurement or a benchmark. The test was performed as specified in ASTM standard E965–15 and the average of four equally spaced diameters was recorded and the macrotexture depth (MTD) of the test pavement surface was calculated using Equation 2-1. As per ISO 13473-1 (2019), MPD is determined by dividing the measured profile into segments of 100 mm in length in the direction of travel and computed using the equation below:

$$\text{MPD (in mm)} = \frac{\text{Peak Level (1st)} + \text{Peak Level (2nd)}}{2} - \text{Average Level} \qquad \text{Equation 6-1}$$

Phoenix utilized ARAN, a fully automated pavement data collection van equipped with a Laser Crack Measurement System (LCMS), and customized distress rating and analysis to a single 3.048 m lane. The survey cross section is divided into five zones: left exterior, left wheel path, center, right wheel path, and right exterior. The wheel paths and the center between the wheel paths are 0.9144 mm and the space outside of the wheel paths to the left or the right edge of the pavement detection zone is 0.1524 m. Although ARAN can extract macrotexture measurements the full width, only the pavement surface texture in the left wheel path and right wheel path are analyzed by Phoenix. The algorithm to compute macrotexture measure, MPD, is based on a “digital sand patch method” which computes the air void-content volume between a three-dimensional rendering of pavement surface and the road surface itself.

The surface macrotexture or surface texture roughness assessment of 20 pavement sections in the Phoenix was performed in the field by the volumetric method and the automated method using ARAN. These 20 sections captured eight different types of preservation treatments Phoenix currently utilizes. At least one macrotexture test per pavement type was performed to generate a full range of macrotexture depth. Fog seal is a light application of emulsified asphalt with or without a rejuvenator that is sprayed so thin that it does not correct pavement surface texture at macro level. Seal coat is a high-performance fiber/mineral reinforced asphalt emulsion blended with polymers and specially graded fine aggregate. Seal coats such as Liquid Road replenish fine aggregates to the existing pavement. Micro seal and slurry seal are carefully designed mixture of asphalt emulsion (which may be polymer-modified or latex polymer emulsified), virgin or reclaimed asphalt pavement (RAP) aggregate, mineral filler, water, and additives and uniformly spread over a properly prepared surface at a single stone thickness. Micro seal with nominal maximum aggregate size (NMAS) of 9.53 mm is applied on high-speed roads and slurry seal with NMAS of 4.75 mm is applied on low-speed roads. Chip seal with precoated chips is called Fractured Aggregate Surface Treatment (FAST). FAST with differing chip gradation can be specified as low volume FAST or high volume FAST. For low volume FAST, the largest sieve opening the aggregate passes is 13 mm and 19 mm sieve opening for the high volume FAST. Thin overlay consists of a mixture of aggregates and terminal blend polymer-modified asphalt rubber binder graded at PG 76–22 TR+. The specified binder content is 6.0% on non-residential streets and 6.2% on residential streets. The asphalt concrete mix uses 13 mm dense graded hot-mix asphalt concrete. The thin overlay pavement thickness is 25 mm on residential streets and 32 mm on non-residential streets.

Field macrotexture measurements in MPD and MTD are reported in Table 6-1. A high MPD or MTD indicates a rough pavement surface texture and a low MPD or MTD indicates a smooth pavement surface texture. MPD ranges from 0.61 mm for fiber slurry seal to 2.97 mm for rough pavement surfaces. MTD ranges from 0.67 mm for thin overlay to 6.93 mm for rough textured pavement surfaces. The lowest MPD is fiber slurry sealed pavement while the lowest MTD is thin overlay pavement. There are three main factors that can be attributed to the differences in average macrotexture depth values. Firstly, MTD is a three-dimensional measure while MPD is a two-dimensional measure. Secondly, MTD is performed manually and MPD is captured using ARAN. Thirdly, MPD is the average macrotexture depth measured along the left and right wheel paths on a given test section while MTD is the average macrotexture depth measured at a random spot anywhere within an evaluation section as specified in ASTM E965. Phoenix's section ID 7320 is the rough pavement section with the highest MPD and MTD values. As shown in Figure 6-1, a strong correlation between MPD and MTD was observed and represented by R^2 of 0.83. A linear relationship established between field MPD and MTD measurements for 20 pavement sections is represented by the equation below:

$$\text{MTD (in mm)} = 2.04 * \text{MPD(in mm)} - 0.03 \qquad \text{Equation 6-2}$$

The effectiveness of preservation treatment in mitigating surface texture defects and the surface macrotexture performance before and after preservation treatments were explored. There were 270 road sections which received a specific preservation treatment less than 18 months ago that were evaluated. They included 49 fog sealed sections, 43 seal coat applied sections, 24 slurry sealed sections, 14 micro sealed sections, 3 high volume FAST applied sections, 6 low volume FAST applied sections, and 131 thin overlay sections. Figure 6-2 shows a box plot of the macrotexture measurements captured by ARAN before and after the preservation treatment. The mean MPD values indicated by the "x" on the box plot are the average MPD values of all sections receiving a specific treatment type and range from MPD of 0.79 mm after thin overlay to MPD of 2.30 mm after high volume FAST. A comparison of the mean MPD before and after treatment indicates an increase in macrotexture after fog seal and FAST applications. While fog seal does not correct pavement surface texture, the aging and oxidation effects occurring during the 7-month to 28-month time elapsed between the before and after treatment condition surveys cause pavement macrotexture depth to increase. Except for the high-volume FAST, which was applied over the chip seal section, the remaining FAST sections were applied on existing overlay or slurry seal pavement sections. Since FAST aggregates are larger in size and more uniform than slurry seal or hot mix dense graded asphalt pavement, an increase in MPD by 63% for high volume FAST and 37% for low volume FAST after treatments was observed. On the other hand, the greatest reduction in pavement macrotexture depth occurred after the slurry seal treatment with a reduction in MPD by 37%. Reductions in MPD were also observed for seal coat, micro seal, and a thin overlay. The smaller section of the box plot indicating a smaller spread of average MPD data is observed for slurry seals, micro seals, low volume FAST, and thin overlay.

Table 6-1: Field Measured MPD and MTD Data

Section ID	MPD (mm)	MTD (mm)	Pavement Surface Type
373210	0.97	0.67	Thin Overlay
7880	0.61	0.94	Fiber Slurry Seal
133901	1.18	1.47	Slurry Seal
39835	0.88	1.08	Micro Seal
43340	1.05	2.56	Micro Seal
10190	1.55	1.32	Seal Coat
40120	0.68	0.86	Seal Coat
10920	1.22	0.99	Fog Seal
334409	0.92	1.33	Fog Seal
82605	1.41	2.16	Seal Coat over Low Volume FAST
73001	2.52	4.33	High Volume FAST
353114	2.51	4.64	High Volume FAST
502001	2.15	2.69	High Volume FAST
7320	2.97	6.93	Rough Surface Texture
7325	2.35	4.66	Rough Surface Texture
15365	2.34	3.69	Rough Surface Texture
40310	2.76	4.19	Rough Surface Texture
40315	2.44	3.57	Rough Surface Texture
42190	2.02	2.87	Rough Surface Texture
42195	1.98	3.21	Rough Surface Texture

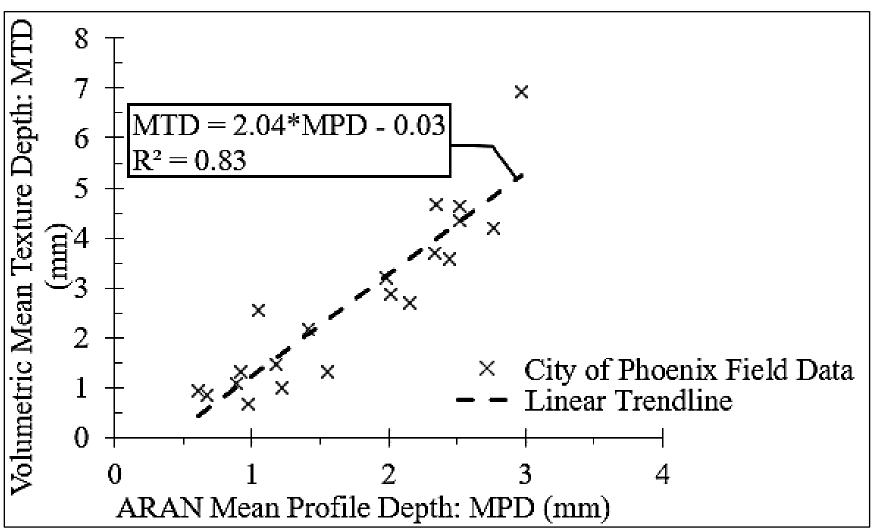
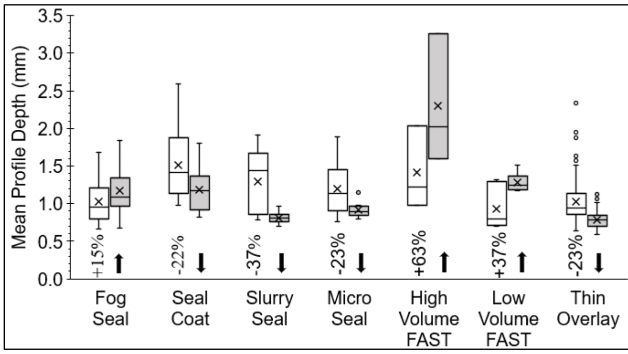


Figure 6-1: Correlation between Macrotexture Using ARAN and Volumetric Method



Main Distress/ Treatment Type	No. of Sections	Mean Profile Depth (mm)		Difference in MPD
		Before Treatment	After Treatment	
Fog Seal	49	1.02	1.17	15%
Seal Coat	43	1.52	1.18	-22%
Slurry Seal	24	1.29	0.81	-37%
Micro Seal	14	1.20	0.92	-23%
High Volume FAST	3	1.41	2.30	63%
Low Volume FAST	6	0.94	1.28	37%
Thin Overlay	131	1.03	0.79	-23%

Figure 6-2: A Comparison of MPD Before and After Treatment

The effectiveness of cape seal and seal coat in mitigating rough texture on the wearing course were also explored. Figure 6-3 shows a rough and pitted pavement with an MPD of 2.76 mm which was treated with a cape seal. Cape seal is an application of micro seal over FAST. A reduction in MPD by 64%, from 2.76 mm before treatment to 1.0 mm, was observed after cape seal. Cape seal corrected the pitted pavement surface by filling and leveling the pavement surface. Although the road was programmed to receive a slurry seal three years later, to address the overwhelming requests from residents to correct the pavement's rough texture, Phoenix's in-house maintenance crew performed a double seal coat application. The double seal coat reduced macrotexture depth by about 31%; from MPD of 2.23 mm to 1.54 mm as shown in Figure 6-4. A specially formulated seal coat, Liquid Road, composed of small and large silica and limestone, and clay ball, is expected to replenish fine aggregates to the existing aged pavement and provide a smoother pavement surface texture. A double seal coat application on a rough pavement improves the pavement texture but does not fill the undulation in the deeply pitted pavement where MPD remains high and mud cracks were observed unexpectedly. Figure 6-5 shows field pictures taken from the top and from the side views of the pavement that had a very rough surface texture and deep pits and after a single coating of Liquid Road and after a double seal coat.

The pavement surface macrotexture for raveled, rough, and fatigue pavements and the change in macrotexture between two consecutive condition surveys were explored. The raveled section shown in Figure 6-6 was treated with Asphalt-Rubber Asphalt Concrete (ARAC) overlay consisting of a mixture of aggregate, mineral admixture, and asphalt-rubber binder (ARB) in 2014.

The specified target binder content was 8.5% and effective void range was 3%±1 for the 75-blow Marshall ARAC mix. Crumb rubber in ARB was at least 18% by weight of the total binder and the maximum size of the crumb rubber was 2 mm. Raveling at the intersections was noticeable a year after the ARAC overlay. The average MPD for the raveled section was 1.29 mm in 2019 and 1.59 mm in 2021 respectively. The average rate of change of MPD within the 23-month period was about 0.3 mm/yr. The rate of change of MPD increased considerably more at the intersection of N 44th St and E Redfield Rd with its rate at 0.7 mm/yr. The average MPD increase for the raveled section was 23% but increased to 48% at the intersection of N 44th St and E Redfield Rd. MPD spikes at the intersections and at the speed hump can be attributed to the stop and go or turning maneuvers, aggravating the pavement surface texture.

The rough textured and polished aggregate section shown in Figure 6-7 was constructed in 1998 and received no subsequent preservation treatment. The average MPD for the rough section was 2.77 mm in 2019 and 2.90 mm in 2021 respectively. The average rate of change of MPD within the 26-month period was 0.06 mm/yr. This aged and pitted pavement surface had already lost binder, fines, and coarse aggregates whose macrotexture depth was increased by 5% between the two survey periods.

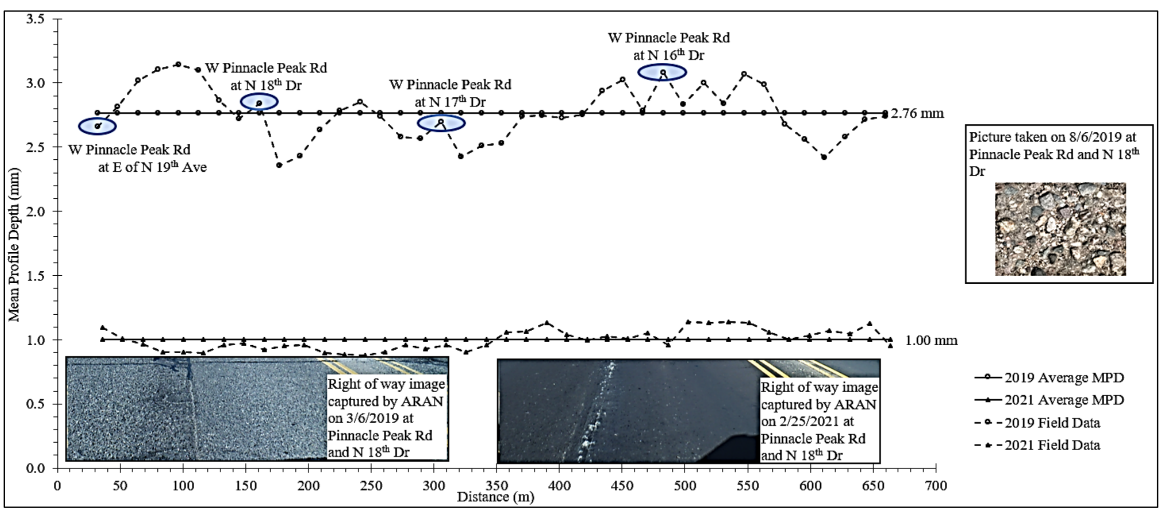


Figure 6-3: Comparison of MPD Values for a Rough Textured Section Before and After a Cape Seal

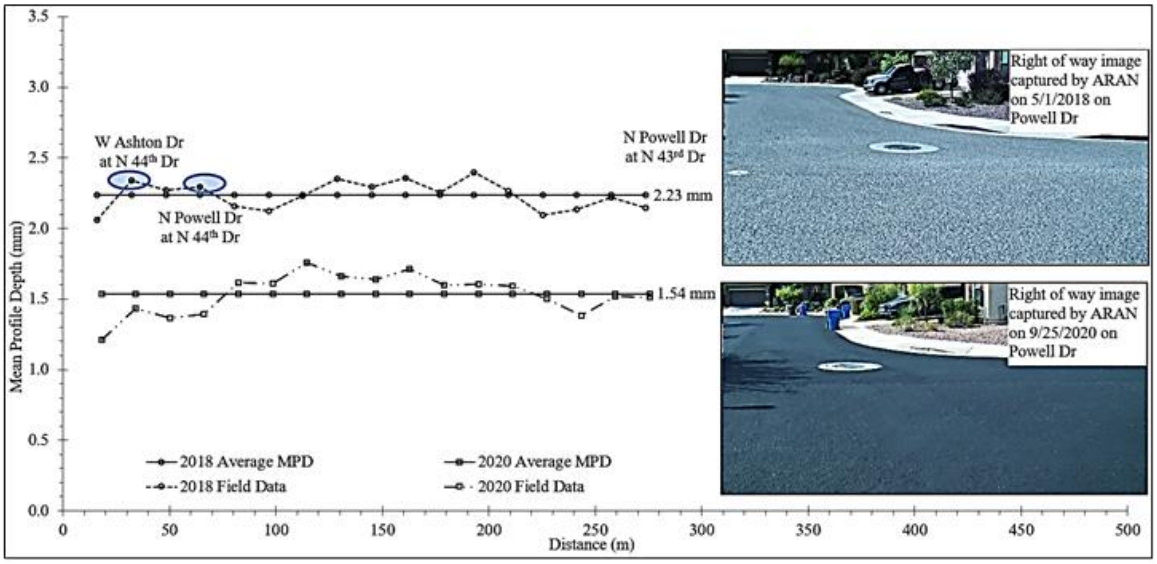


Figure 6-4: Comparison of MPD Values for a Rough Textured Section Before and After a Seal Coat Application

Figure 6-5: Pavement Surface Before and After the First Coat of Seal Coat Application (Left and Center Images) and the Final Surface After the Double Seal Coat (Right Image)

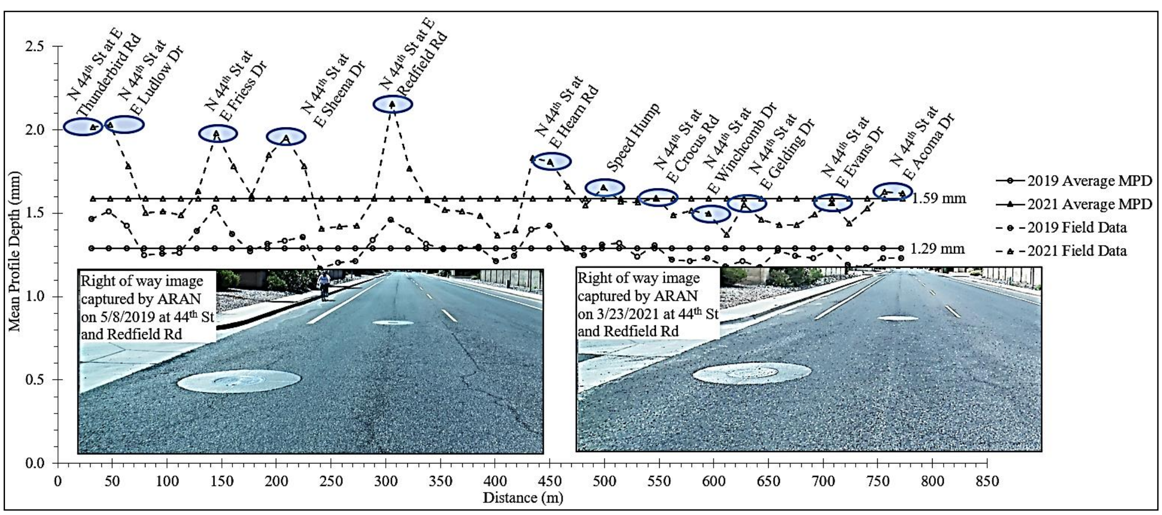


Figure 6-6: Comparison of 2019 and 2021 Field MPD Values for a Raveled Section

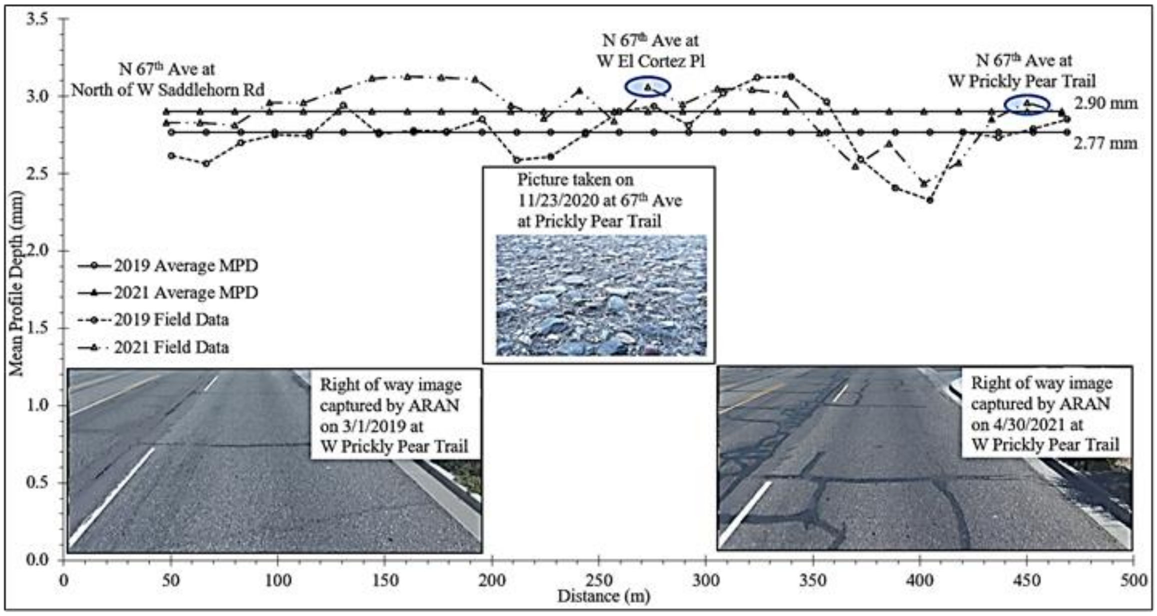


Figure 6-7: Comparison of 2019 and 2021 Field MPD Values for a Rough Section

The pavement section shown in Figure 6-8 was widened in 1998 with no additional maintenance activity performed on the existing pavement. The macrotexture condition assessments were performed on the fatigue section and the average MPD was 1.23 mm in 2019 and 1.24 mm in 2021 respectively. The change in pavement macrotexture depth is negligible, less than 1%, for the fatigue section. The average rate of change of MPD within the 23-month period is about 0.01 mm/yr.

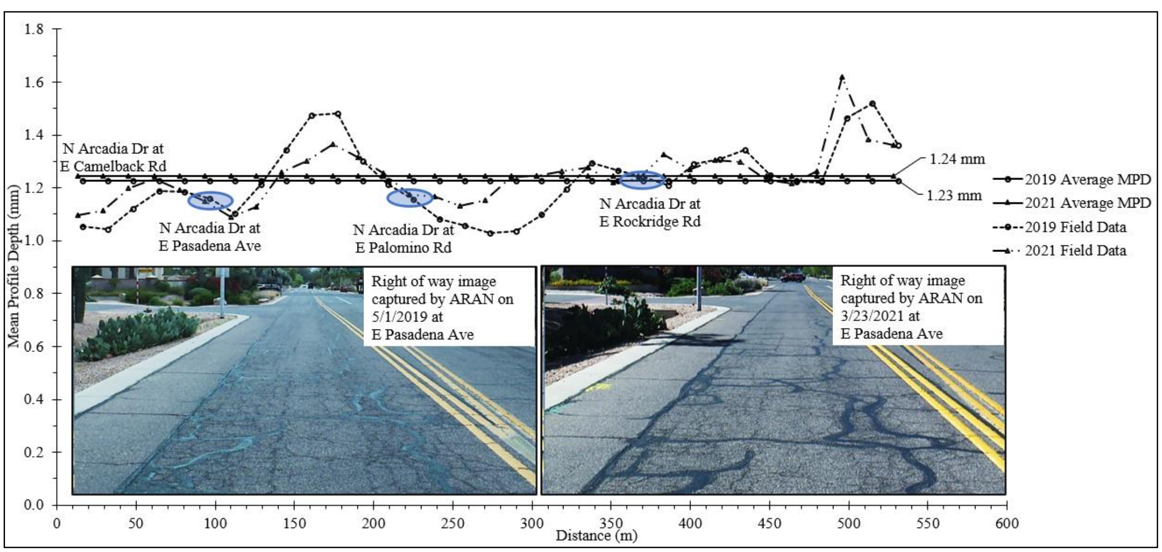


Figure 6-8: Comparison of 2019 and 2021 Field MPD Values for a Fatigue Section

6.4 PAVEMENT SURFACE MACROTEXTURE PERFORMANCE MODEL

The objectives of the pavement performance model are to allow agencies to predict pavement condition in the future, to develop annual pavement maintenance programs, and to compare the performance of different preservation treatments. Thus, the pavement performance model needs to be reliable, accurate, and up to date. Iuele (2016) mentioned the difficulty in estimating the texture deterioration rate. Her study was based on four different dense graded friction courses laid on four road sections in Cosenza, Italy. The pavement surface texture for the test sections were measured and monitored immediately after construction and every 6 months for up to 18 months after the construction. The City of Phoenix data, which included 13 thin overlay sections that had records of at least two surveys performed in less than 18 months, also supported Iuele's (2016) finding. As shown in Figure 6-9, MPD increased right after an overlay and then decreased after 0.16 yr. Then another increase in MPD after 0.2 yr. was followed by another decrease in MPD.

Figure 6-9: Mean Profile Depth after Thin Overlay

Since the City of Phoenix acquired the ARAN 9000 model in November 2017, the macrotexture data was limited. Therefore, the Long-Term Pavement Performance (LTPP) database was used to investigate the macrotexture performance right after overlay and the performance over time after overlay and chip seal. There were 441 sections out of 1,807 total LTPP asphalt concrete test sections for which macrotexture surveys were performed between April 21, 2013, and November 14, 2019. The macrotexture database went through a rigorous data cleaning procedure where MPD was evaluated and sections with only one MPD survey record were removed. As shown in Figure 6-10, a similar variation in macrotexture performance was observed for thick hot-mix dense graded asphalt overlay sections and a gradual increase in macrotexture was observed 18 months after the overlay. Research performed by Iuele (2016) also noted a similar surface texture characteristic on four test sites during the first 18 months after dense graded friction courses were applied. She attributed the initial increase in macrotexture depth to the loss of bitumen film from the aggregate surface. The bond between the aggregate and the binder depended on the asphalt binder in the asphalt mixture and the nature of the aggregate. Instead of vehicular traffic load smoothing and kneading the asphalt binder, because of a lower stripping resistance aggregate, the bitumen film was removed from the aggregate. It was then followed by a substantial decrease in the macrotexture depth due to the smoothing and polishing effect from the traffic loading over time as well as dust and oil buildups. With its compaction-like action, the traffic loading induced binder smearing and binder migration which filled the voids and thereby decreased the macrotexture depth. Another significant increase in macrotexture a year after construction was attributed to the removal of migrated binder from trafficking. With such great variation in macrotexture depth during the first several months after construction, estimating the rate of macrotexture deterioration was indeed difficult. Therefore, data points for which the rate of change of MPD rapidly decreased or increased after preservation treatments were removed from consideration and macrotexture data collected 12 months after overlay and sections with increasing MPD over time were considered for the study.

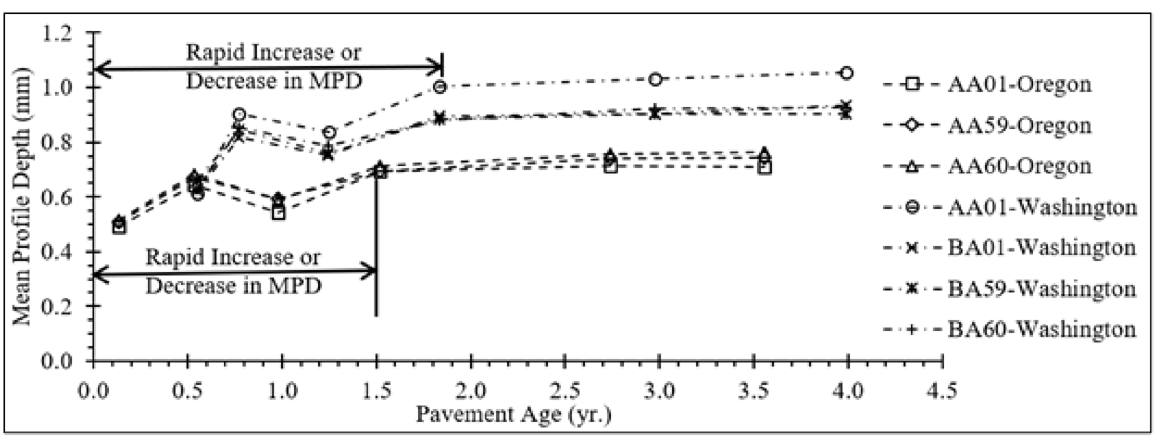


Figure 6-10: Mean Profile Depth (mm) for Hot-Mix Dense Graded Asphalt Overlay Surface

The macrotexture depth for hot-mix dense graded asphalt pavement increases over time while the macrotexture depth for chip seals decreases over time. The environment alone can cause the asphalt pavement to age and oxidize over time. As the pavement ages and oxidizes, the asphalt surface starts losing binder and then fine aggregates. Traffic loading also affects the pavement surface texture by causing bitumen film to wear off, fine aggregates to lose, and coarse aggregates to polish. The extent and rate of aggregate loss is dependent on the asphalt pavement mixture. Beside pavement surface macrotexture contributions to roadway safety and noise, its characteristic is indicative of pavement surface wear over time or premature pavement defects. Therefore, it is critical to periodically survey pavement surface texture in the field at the flow of the traffic using a reliable and practical pavement surface texture assessment method, so pavement surface texture can be monitored, and surface texture issues can be detected and addressed appropriately.

Due to the data availability, the MPD performance model was developed using 34 hot mix dense graded thin overlay and 37 chip seal sections from the LTPP database. The surface texture depth for the thin overlay was assessed approximately between 14 months to 20 years after the overlay. The field texture surveys for the chip seal were performed approximately between 11 months to 19 years after the treatment. The field measured MPD ranges from 0.50 mm to 1.50 mm for hot-mix dense graded thin overlay and 0.85 mm to 2.30 mm for chip seals. Gradual increase in pavement surface texture depth indicator, MPD, over time for hot-mix dense graded asphalt pavement and the gradual decrease in MPD over time for chip seals can be captured by the power function. Uz and Gökalp’s (2017) concluded that the macrotexture depth for the chip seal increased as the chip size increased. The traffic load working and kneading to achieve the desired chip embedment, MPD, is expected to decrease over time for chip seals. The expressions for MPD and the rate of change of MPD (MPD’) are represented by Equation 6-3 and Equation 6-4:

$$MPD\ (in\ mm) = \propto + \beta * T^{\gamma} \quad \text{Equation 6-3}$$

$$MPD'\ (in\ mm) = \beta * \gamma * T^{(\gamma - 1)} \quad \text{Equation 6-4}$$

where: T is adjusted time (in years) since the last major construction or preservation treatment to best fit the power function and α, β and γ are shape parameters of the power function. The shape parameters for thin overlay are $\alpha = 0.51$, $\beta = 0.05$, and $\gamma = 1.15$ while the shape parameters for chip seal are $\alpha = -16.56$, $\beta = 18.78$, and $\gamma = -0.03$ respectively. The pavement surface texture-based performance models based on the historical MPD data for the thin hot-mix dense graded asphalt overlay and chip seal are shown in Figure 6-11. The field macrotexture depths were represented by the triangle markers for overlay and diamond markers for chip seals. Comparing the standard error ratio for the pavement surface texture models, the model for overlay pavement was slightly more accurate with S_e/S_y of 0.26 and its corresponding R^2 of 0.96 than the model for chip seal with a slightly higher standard error ratio with S_e/S_y of 0.31 and its corresponding R^2 of 0.94. Since R^2 denoting a measure of an accuracy of the pavement macrotexture performance model is high, the models are highly correlated to the field MPD data.

A high pavement texture depth is not suggestive of texture issue but a higher-than-normal rate of change of MPD is indicative of raveling, and a lower-than-normal rate of change of MPD is indicative of bleeding. A normal thin overlay or chip seal is expected to follow their respective rate of change of MPD trend which was derived from the pavement surface texture performance models and shown in Figure 6-12. Figure 6-12 also displayed 20 data points for each unique LTPP section which received thin overlay treatment and 5 data points for sections which received chip seal. Each data point represented the rate of change of MPD and was determined by dividing the difference in MPD measurements of a section by the time difference between the two MPD survey dates. These raveled and bleeding sections were gathered from the comments on the LTPP field distress survey forms and verified with the distress images since raveling or bleeding were noted but not always rated. Since there was only one thin overlay section that was bleeding and no section that was raveling, a few thick overlay sections were considered in addition. This does not mean that thin overlay pavements do not ravel or bleed but rather indicates limitations on data availability. There were ten thick overlay sections that were bleeding and another nine sections that were raveling. As shown in Figure 6-12, the rate of change of MPD for all eleven bleeding sections fell below the thin overlay rate of change of MPD performance curve and all nine raveled sections fell above the thin overlay rate of change of MPD performance curve. Similarly, four filled diamond points, which fell above the rate of change of the MPD performance curve, denoted three raveled chip seal sections. The rate of change of MPD for a chip seal section that was bleeding was represented by the unfilled diamond marker and fell just below the pavement surface texture performance curve.

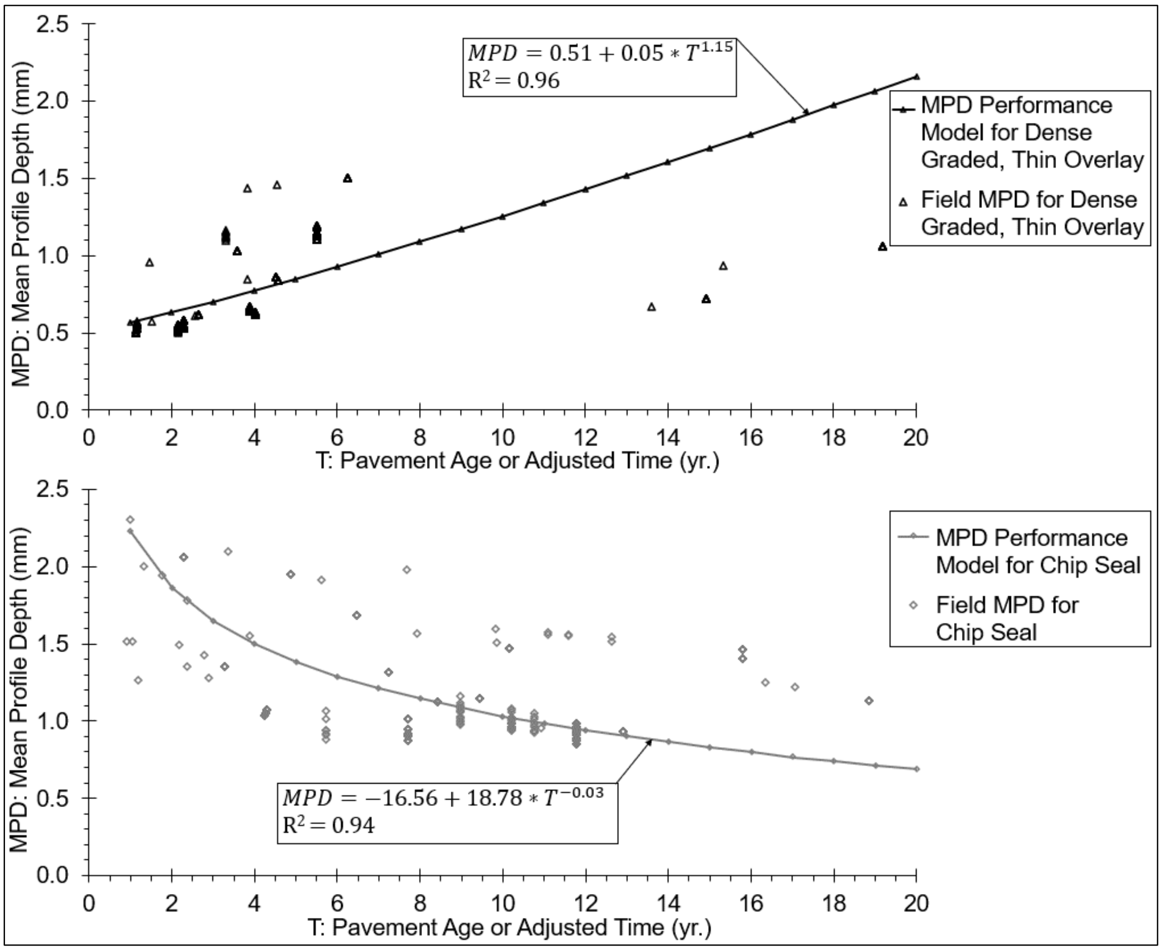


Figure 6-11: MPD Based Pavement Surface Texture Performance Curves

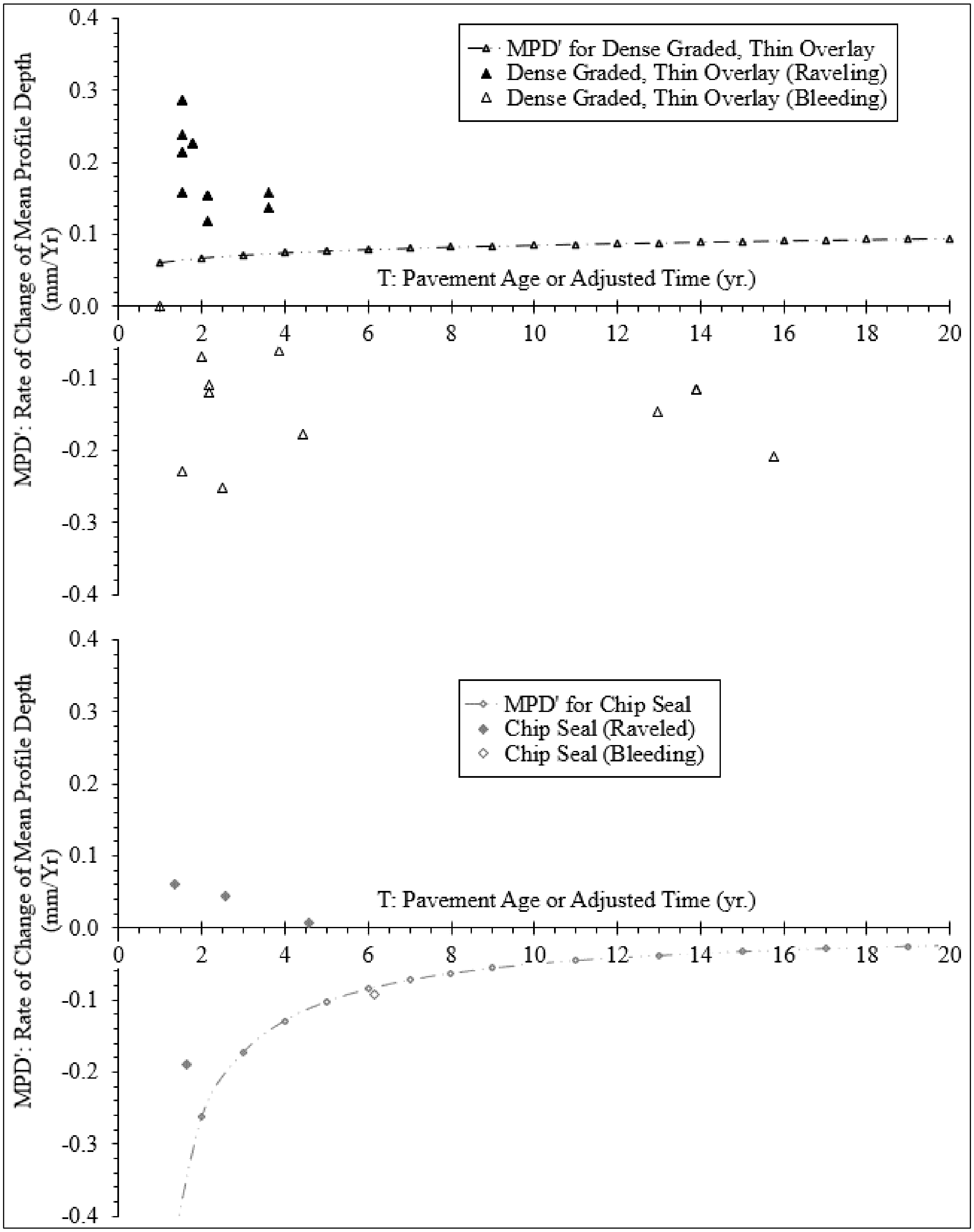


Figure 6-12:The Rate of Change of MPD Based on Pavement Surface Texture Performance Curves

6.5 PAVEMENT PRESERVATION TREATMENT STRATEGY

It is recommended that new pavements or pavements that receive preservation treatment undergo a full year of summer-winter cycle even before considering a light preservation treatment such as fog seal. The threshold values to trigger a specific preservation treatment were not determined based on the pavement age but instead by evaluating the macrotexture measure of an existing pavement surface. The pavement surface macrotexture indicator, MPD, was investigated to be integrated into the pavement surface texture treatment recommendation strategy so pavement with surface texture issues can be addressed accordingly. There were 43 hot-mix dense graded overlay sections investigated of which seven were thick overlays. There were 33 sections that did not ravel nor bleed but four of them had high MPD. There were three raveled and seven bleeding sections. As shown in Figure 6-13, the solid line with triangle markers represented the MPD performance curve for thin overlay and the dash, dot, dot line with the triangle markers represented the rate of change of MPD. The MPD for hot-mix dense graded thin overlay pavement surface texture ranged from 0.5 mm to 1.5 mm. LTPP sections with an MPD of approximately 1.2 mm or higher were represented by the lines with the circle markers. Although MPD of 1.2 mm and higher exhibited a rougher surface texture, the rate of change of MPD, represented by the circle makers, were below the rate of change of MPD performance curve and were still above the rate of change of MPD of zero. Therefore, besides exhibiting rougher surface texture, no raveling or bleeding were observed on these sections. Since pavement surface macrotexture is dictated by the asphalt binder and aggregate composition in the overlay mixture, a higher MPD or rougher surface texture does not necessarily indicate raveling and a lower MPD or smoother surface texture does not necessarily indicate bleeding.

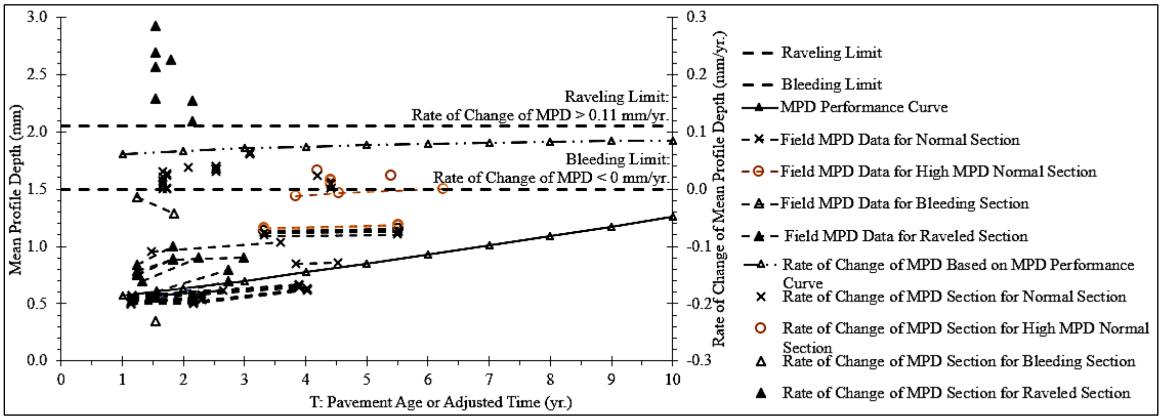


Figure 6-13: Pavement Surface Texture Thresholds for Hot-Mix Dense Graded Overlay Pavement

The rate of change of MPD is a better measure to use in establishing bleeding and raveling limits. The MPD for a bleeding overlay section represented by the dashed line with unfilled triangle markers decreased over time and the rate of change of MPD at approximately −0.23 mm/yr. fell below zero. The rate of change of MPD for dense graded overlay without texture issues gradually increased over time and thus the rate of change of MPD falling below zero represented a reduction in macrotexture depth over time and denoted bleeding. The hot-mix dense graded thick overlay section was added to Figure 6-13, to illustrate MPD and the rate of change of MPD for a bleeding section. Even with the limited data, using engineering judgment and available historical data, the rate of change of MPD less than 0 mm/yr. can be established as the threshold for bleeding. Since there was only one raveled thin overlay section, six thick overlay sections that were noted in the field as raveling were also evaluated to determine the threshold for raveling. The MPD for the seven raveled hot-mix dense graded overlay LTPP pavement sections was not significantly higher than the rest of the overlay pavement section. However, the lowest rate of change of MPD for the raveled sections was 0.11 mm/yr. and fell above the rate of change of MPD performance curve. There were 16 chip seal treated LTPP sections evaluated as shown in Figure 6-14. There were eleven sections without texture issues, two raveled sections, and three bleeding sections. MPD for chip seal sections ranged from 0.67 mm to 2.1 mm. Generally, MPD is expected to decrease over time for the chip seal, but MPD was observed to increase for the raveled chip seal. Therefore, the rate of change of MPD greater than zero was set as the threshold for raveling. Based on the field MPD data and a review of the distress survey, the bleeding limit was established as the rate of change of MPD lower than −0.15 mm/yr.

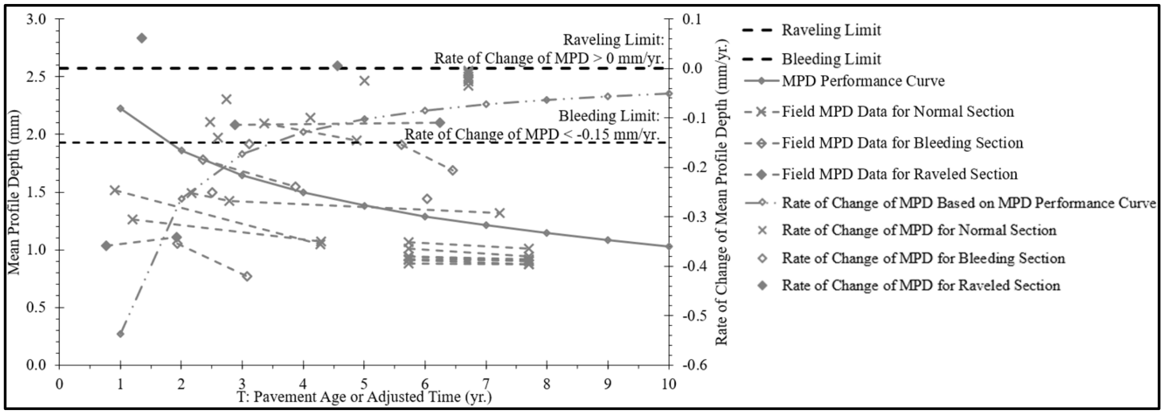


Figure 6-14: Pavement Surface Texture Thresholds for Chip Seal

Pavement maintenance strategies are designed to always keep the pavement above a target acceptable level and to prevent pavement from requiring rehabilitation (Peterson, 1981). The preservation treatment selection decision tree shown on Figure 6-15 was developed from analyzing a meaningful performance measure, surface macrotexture. This macrotexture performance measure can provide quantifiable benefits associated with preservation treatment applications and trackable pavement performance over time. It can also be used to trigger surface treatment. On a structurally sound pavement that is raveling, low-cost surface treatments such as seal coat, slurry seal and micro seal can be used to restore existing asphalt pavement surface texture and retard further disintegration or dislodging of fine and coarse aggregates. When raveling is severe and affects pavement structure, a more extensive treatment is required to restore pavement structure. A mild bleeding on a structurally sound pavement can be addressed by spreading the blotting material such as sand to soak up excess binder or by slurry seal for more severe bleeding.

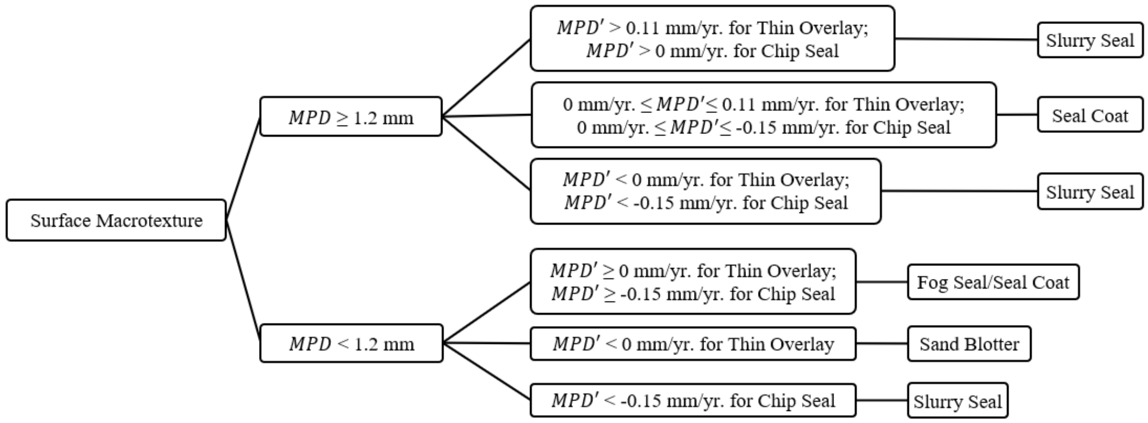


Figure 6-15: Preservation Treatment Selection Decision Tree

Li et al. (2017) performed the effects of pavement macrotexture on bicycle ride quality and based on the survey responses from 155 bicycle club members, slurry seal on city streets was highly acceptable. Therefore, an MPD of 1.2 mm for the slurry seal was selected to delineate the rough pavement surface texture. For a pavement section that has rough surface texture and is raveled, MPD is greater than or equal to 1.2 mm, and the rate of change of MPD is greater than 0.11 mm/yr. for thin hot-mix dense graded asphalt overlay and 0 mm/yr. for chip seals. Slurry seal is recommended to mitigate surface texture roughness and raveling. An existing oxidized pavement with MPD greater than or equal to 1.2 mm, and rate of change of MPD between 0 and 0.11 mm/yr. for overlay or between 0 and −0.15 mm/yr. for chip seal is considered rough but has not raveled or bled yet that seal coat is recommended to retard raveling potential in the future. A pavement section with MPD greater than or equal to 1.2 mm, and the rate of change of MPD less than 0 mm/yr. for thin overlay or −0.15 mm/yr. for chip seal is considered bleeding and missing aggregates, a slurry seal is recommended. A pavement with MPD less than 1.2 mm, and the rate of change of MPD greater than or equal to 0 mm/yr. for overlay or −0.15 mm/yr. for the chip seals may have started raveling but have not significantly lost aggregates yet; a fog seal or seal coat is recommended to lock aggregate in place and prevent further raveling. A hot-mix dense graded asphalt overlay section that is bleeding with MPD less than 1.2 mm and the rate of change of MPD less than 0 mm/yr. can be treated using a sand blotter. A chip seal treated pavement section with an MPD less than 1.2 mm and the rate of change of MPD less than −0.15 mm/yr. is considered bleeding and has lost chips considerably so that a slurry seal is recommended to provide a new wearing course. The macrotexture indicator, MPD, was used to objectively detect raveling and bleeding as well as trigger preservation treatments to mitigate pavement surface texture issues. However, agencies can potentially use a different macrotexture indicator such as MTD and adjust the macrotexture and the rate of change of macrotexture depth limits to reflect the local network performance and to tailor to the budget scenario. Therefore, the pavement surface macrotexture can be integrated into the pavement management system and used in optimizing pavement preservation treatment recommendation strategies.

6.6 SUMMARY OF FINDINGS AND CONCLUSIONS

This chapter presented a methodology from analyzing the existing pavement surface macrotexture performance measure to developing the pavement performance model and establishing a preservation treatment selection strategy to address texture related distresses. Although the automated macrotexture detection method which can be performed at the flow of the traffic is not inexpensive currently, in the near future with improvements in Light Detection And Ranging (LiDAR) and camera, an assessment of pavement macrotexture can be performed using a smartphone. Data limitation only allowed this study to present performance models for thin hot-mix dense graded asphalt overlay and chip seals. Therefore, a periodic assessment of pavement macrotexture for at least three rounds of survey can be used to develop pavement macrotexture performance models for other types of pavements. Further research, using additional data, is necessary in this area.

The primary purpose of a pavement preservation program is to keep the good road in good condition for an extended period of time. A successful implementation of the pavement preservation program allows an agency to provide guidance in the selection and timing of the preservation treatments for its street network considering the budget, to objectively monitor the performance of a specific treatment over its service life, and to measure the cost-effectiveness of the preservation treatment. A common practice for the pavement preservation treatment program has been applying the right preservation treatment on the right road at the right time. Preservation treatments are known to extend the service life of the pavement by protecting the good pavement from rapid deterioration at a lower cost compared to the cost of rehabilitation for the life of the pavement. There are several preservation treatments available and each with its unique intended purpose and benefits.

The major findings from this research work are highlighted below:

1. Pavement surface macrotexture for various pavement surface types was different: macrotexture depth for fiber slurry seal was the lowest with MPD of 0.61 mm and the highest with MPD of 2.97 mm for the pitted and rough textured pavement.
2. Pavement surface macrotexture indicators, MTD, measured using the manual method, and MPD, measured using the automated method, were strongly correlated.
3. An analysis of before and after preservation treatments demonstrated a 37% reduction in MPD for slurry seal and 63% increase in MPD after FAST.
4. In an approximately two-year period, an increase in MPD for a raveled pavement was 23% and was less than 1% for the fatigue pavement. The increase in MPD for a pitted pavement which had already lost binder and fine aggregate was about 5%.
5. Based on a review of the pavement surface macrotexture performance after an overlay, during the first 18 months, pavement surface texture may go through a rapid increase and rapid decrease in macrotexture depth due to the traffic, aggregate gradation, asphalt type, and mixture composition.
6. The pavement surface macrotexture performance models developed from the historical MPD data from LTPP database showed a gradual increase in MPD over time for a hot-mix dense graded asphalt overlay and a gradual decrease in MPD over time for chip seals.
7. The rate of change of MPD, derived from the MPD performance model, can be used to objectively rate raveling and bleeding.
8. Since pavement surface macrotexture greater than MPD of 1.2 mm measured using LCMS is rougher than slurry seal surface, MPD greater than 1.2 mm is defined as a rough pavement surface texture that may or may not be raveled

9. Based on pavement surface macrotexture performance measures, a preservation treatment decision tree to address pavement surface texture issues can be developed and incorporated into the preservation treatment program.

CHAPTER 7

EVALUATING THE EFFECTIVENESS OF PAVEMENT PRESERVATION TREATMENT

7.1 INTRODUCTION

Pavement preservation treatment is said to work best when it is applied on the pavement a year before it needs the treatment. The limited tax dollars invested in the pavement management program stretches further when preservation treatments are deployed as preventive maintenance measures and not as reactive maintenance measures. The slogan the right treatment, on the right road, at the right time is an aspired goal for transportation agencies but budget, policies, and the public have undeniable influences on the success of achieving that very goal. Equally critical to the understanding of the major pavement distresses in the agency's street network is the understanding of available pavement preservation treatments. Based on the major pavement distresses observed in the City of Phoenix street network, the primary preservation treatments in the City's toolbox consists of fog seal, seal coat, slurry seal, micro seal, FAST, and thin overlay. Crack seal is used as a preparatory treatment to the primary preservation treatments but never a standalone treatment since 2018 merely because of the public perception of the appearance of the crack seal. Pavements that require cracks to be sealed with a crack seal to prevent moisture intrusion also receive an application of fog seal a few months after cracks are sealed, preferably after the crack seal went through a summer heat cycle, to provide a more appealing appearance.

The objectives of this portion of the research are: (1) to evaluate the effectiveness of the pavement preservation treatments the City of Phoenix used to ensure the right treatment is applied to the right street at the right time and (2) to investigate factors affecting the effectiveness of the treatment.

7.2 PAVEMENT PRESERVATION TREATMENT

7.2.1 Treatment Types in the City of Phoenix Toolbox

Regardless of pavement preservation treatment type, they are as good as the underlying pavement, therefore an accurate evaluation of the pavement condition supersedes the selection of the pavement preservation treatment type. The analysis software dTIMS is used to optimize and assign a treatment type based on the current pavement condition and available budget. An engineer then takes the dTIMS recommended treatment plan and location to the field for validation of the treatment type. There are several pavement treatments the City of Phoenix uses to preserve the life of its street network. These treatments range from the heaviest and most expensive and extensive treatment, thin overlay, to the lightest treatment, fog seal. In general, fog seals are applied on pavement in excellent to good condition. Seal coat is applied to pavement in good condition. Slurry seal and micro seal are applied on good to fair pavement condition and slurry seal is applied on low-speed road and micro seal on high-speed road. FAST and thin overlay are applied to pavement in fair to poor condition and FAST use is restricted to industrial streets.

Except for the newer pavement exhibiting cracks less than 0.006 m (¼ in) wide, every street that is programmed to receive a preservation treatment is crack sealed at least 3 months, preferably after going through a summer cycle, before the primary treatment is applied. Type 3 Polyflex crack sealant such as Crafco Polyflex Type 3 is hot applied to fill and seal cracks in asphalt pavements that have crack opening width between 6 mm (¼ in) and 38 mm (1.5 in) at the time of the application. However, areas with fatigue cracks and the pavement edge areas which are milled in preparation for thin overlay treatment are excluded from crack sealing. Cracks are cleaned but not routed before applying crack sealant and deep cracks are applied in multiple lifts to fill the crack. For wider cracks ranging from 38 mm (1.5 in) to 0.1 m (4 in), a heavier material, hot applied mastic repair material such as Deery Level & Go Repair Mastic is used. The maximum thickness of each lift of mastic applied is 102 mm (4 in) and cracks with opening width greater than 102 mm (4 in) require filling the void with aggregate chips.

Fog seals such as Cationic Quick Set- Tire Rubber Modified (CQS-1H-TR), Optipave, and Polymer Modified Rejuvenating Emulsion (PMRE) are a light application of emulsified asphalt applied to an existing asphalt surface where penetration of the emulsion can be expected but is structurally sound. Fog seal is applied on weathered or oxidized asphalt surfaces to improve the surface appearance, seal minor cracks and surface voids, and prevent raveling (due to segregation or poor compaction). The all-inclusive unit cost for fog seal on residential and non-residential streets is about \$18.84/m^2 (\$1.75/ft^2) and \$19.48/m^2 (\$1.81/ft^2). The all-inclusive unit cost includes the cost of the fog seal, crack seal, and cost associated with the construction. Two years of life extension is expected from a fog seal under an optimal pavement condition.

Seal coats such as Liquid Road and Polymer Modified MasterSeal (PMM) are a high-performance fiber/mineral reinforced asphalt emulsion sealcoat blended with polymers and specially graded fine aggregate applied to pavement surfaces in good condition. Seal coat is intended to replenish the binder that is lost through oxidation and weathering. Moreover, seal coat has been applied to pavements that recently received low volume FAST to avoid aggregate loss and to provide a smoother pavement. The unit cost for seal coat and crack seal preparatory treatment is about \$32.40/m^2 (\$3.01/ft^2). Because of its lower surface friction, seal coat is only used on low-speed roads such as residential streets. Four to seven years of life extension is expected from a seal coat application under an optimal pavement condition.

Micro seal and slurry seal are surface treatments consisting of a carefully designed mixture of asphalt emulsion (which may be polymer-modified or latex polymer emulsified), mineral aggregate, water, and additives; proportioned, mixed, and uniformly spread over a properly prepared surface at a single stone thickness. Micro seal is used on high-speed roads and slurry seal is used on low-speed roads. Micro seal Type II and Type III differ in the gradation of the mineral aggregate and Type II micro seal with a higher percent of aggregate passing No. 4 is used on a higher speed road with bicycle traffic while Type III micro seal is used on road without bicycle traffic. The all-inclusive unit cost for slurry seal on residential street and micro seal on non-residential street are about \$34.55/m^2 (\$3.21/ft^2) and \$83.10/m^2 (\$7.72/ft^2) respectively. The all-inclusive unit cost includes the cost of the fog seal, crack seal, and cost associated with the construction. The unit cost for a micro seal is substantially higher because it also includes the cost to upgrade the pedestrian ramp to meet the ADA standard. Seven years of life extension is expected from a slurry seal or micro seal treatment under an optimal pavement condition.

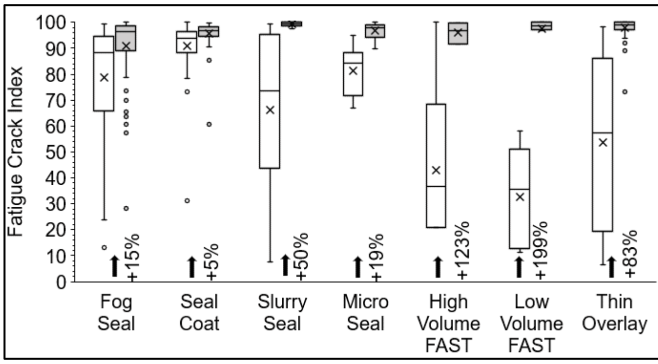
Thin overlay and FAST are applied on streets that are in poor pavement surface condition but are still structurally sound. Since thin overlay is expensive, FAST is used on industrial roads. FAST are precoated chips with low volume and high volume FAST having different chip gradation. As their names indicate, the low volume FAST gradation is specified for application on low volume traffic areas and high volume FAST for use on high volume traffic areas. For low volume FAST, the largest sieve opening the aggregate passes is 13 mm (½ in) while for the high volume FAST, it is 19 mm (¾ in) sieve opening. The cost of FAST which includes crack seal preparatory work is \$77.18/m^2 (\$7.17/ft^2).

Thin overlay consists of a mixture of aggregates and terminal blend polymer-modified asphalt rubber binder graded at PG 76-22 TR+. The specified binder content is 6.0% on non-residential streets and 6.2% on residential streets. The asphalt concrete mix used is 13 mm (½ in) dense graded hot-mix asphalt concrete. The edges are milled approximately 19 mm (¾ in) below the existing gutter on residential streets and 25 mm (1 in) below the gutter on non-residential streets to avoid built up. The milling is tapered to 0 m (0 in) for proper tie-in at 1.8 m (6 ft) from the gutter lip on residential streets and 3.7 m (12 ft) from the gutter lip on non-residential streets. The design overlay pavement thickness is 25 mm (1 in) on residential streets and 32 mm (1¼ in) on non-residential streets. The cost of thin overlay which includes the material and application of crack seal and thin overlay and upgrading sidewalk ramp is \$185.25/m^2 (\$17.21/ft^2) for residential street and \$196.01/m^2 (\$18.21/ft^2) for non-residential street. Ten years of life extension is expected from a FAST or thin overlay treatment under an optimal pavement condition.

7.3 EVALUATING TREATMENT BENEFIT POST APPLICATION

7.3.1 Evaluation of Cracking Distress after Preservation Treatment

An assessment of pavement condition after receiving preservation treatments was performed. A total of 270 streets were evaluated: 50 sections that received fog seal, 41 sections that received seal coat, 23 sections that received slurry seal, 14 that received micro seal, 4 sections that received high volume FAST, 7 sections that received low volume FAST, and 131 sections that received thin overlay. As shown in Figure 7-1 all the preservation treatments improve the fatigue crack index to some extent and fatigue crack index after any type of treatment is greater than 91. Fatigue crack index improvement is lowest on seal coat applied pavements, with only 5% improvement because the pavement already has a high fatigue crack index before treatment. Pavements recommended for FAST and overlay with the lowest fatigue crack index, improve the most with greater than 83% improvement. A small amount of fatigue cracking contributing to the fatigue crack index of 98 rather than 100 is attributed to the cracks in the curb, concrete manhole cover, and valley gutter that the pavement collection system detected and classified as fatigue cracks. Figure 7-2 illustrates fatigue cracking detected by the ARAN and classified by Vision software as fatigue cracks.



Main Distress/ Treatment Type	Fatigue Crack Index Before Treatment	Fatigue Crack Index After Treatment	Difference in Fatigue Crack Index
Fog Seal	79	91	15%
Seal Coat	91	96	5%
Slurry Seal	66	99	50%
Micro Seal	81	97	19%
High Volume FAST	43	96	123%
Low Volume FAST	33	98	199%
Thin Overlay	54	98	83%

Figure 7-1: A Comparison of Fatigue Crack Index Before and After Treatment

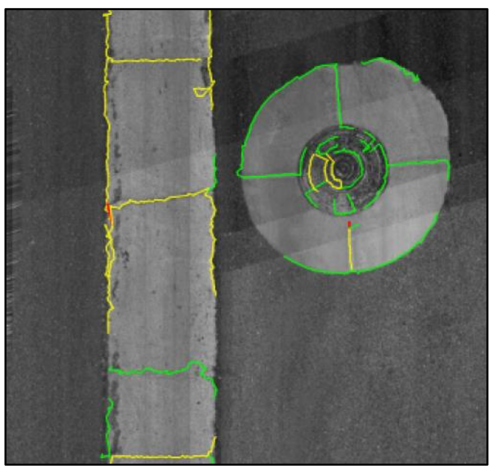
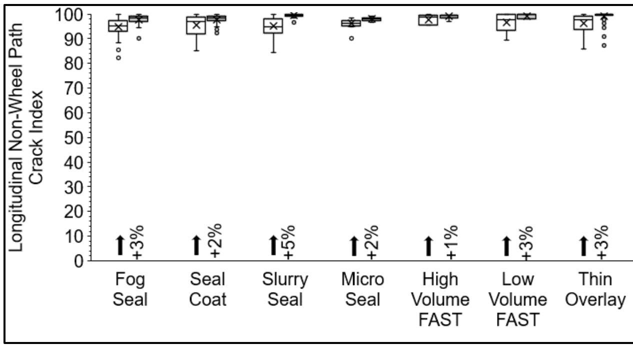


Figure 7-2: Fatigue Crack Map for Thin Overlay Pavement

Figure 7-3 shows longitudinal non-wheel path crack index before and after treatments. The longitudinal non-wheel path crack index before and after treatment are both equal to or greater than 95. With the preservation treatments, there is still a minimal improvement in the longitudinal non-wheel path crack index.

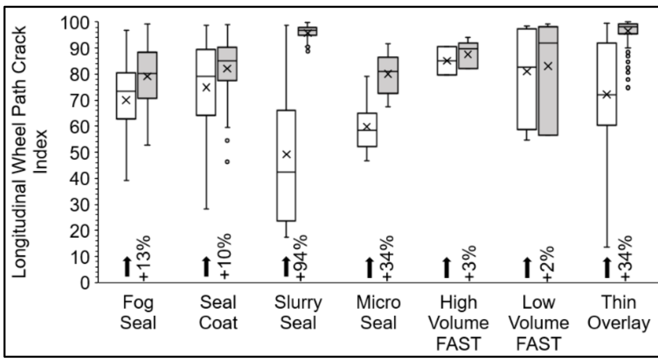


Main Distress/ Treatment Type	Longitudinal Non-Wheel Path Crack Index Before Treatment	Longitudinal Non-Wheel Path Crack Index After Treatment	Difference in Longitudinal Non-Wheel Path Crack Index
Fog Seal	95	98	3%
Seal Coat	96	98	2%
Slurry Seal	95	99	5%
Micro Seal	96	98	2%
High Volume FAST	98	99	1%
Low Volume FAST	96	99	3%
Thin Overlay	96	99	3%

□ Longitudinal Non-Wheel Path Crack Index Before Treatment
▣ Longitudinal Non-Wheel Path Crack Index After Treatment
× Mean of Longitudinal Non-Wheel Path Crack Index
∘ Outlier

Figure 7-3: A Comparison of Longitudinal Non-Wheel Path Crack Index Before and After Treatment

Figure 7-4 shows longitudinal wheel path crack index before and after treatments. With the preservation treatment, there are improvements in the longitudinal wheel path crack index. Smallest improvement in longitudinal wheel path crack index is observed after FAST application. As shown in Figure 7-5, the cracks in the yellow rectangle are longitudinal wheel path cracks observed after FAST. The cracks detected were cracks not sealed and reflected through FAST.



Main Distress/ Treatment Type	Longitudinal Wheel Path Crack Index Before Treatment	Longitudinal Wheel Path Crack Index After Treatment	Difference in Longitudinal Wheel Path Crack Index
Fog Seal	70	79	13%
Seal Coat	75	82	10%
Slurry Seal	49	96	94%
Micro Seal	60	80	34%
High Volume FAST	85	88	3%
Low Volume FAST	81	83	2%
Thin Overlay	72	97	34%

□ Longitudinal Wheel Path Crack Index Before Treatment
▣ Longitudinal Wheel Path Crack Index After Treatment
× Mean of Longitudinal Wheel Path Crack Index
∘ Outlier

Figure 7-4: A Comparison of Longitudinal Wheel Path Crack Index Before and After Treatment

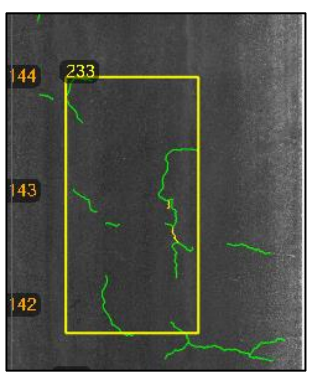
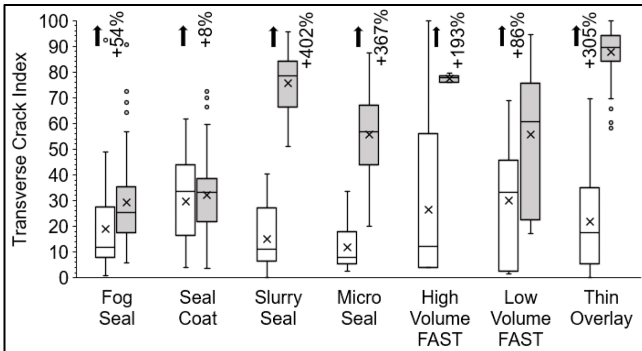


Figure 7-5: Longitudinal Crack Map of FAST Applied Pavement

Figure 7-6 shows the transverse crack index before and after preservation treatments. Except for the pavements that received seal coat, pavement receiving preservation treatments improved the transverse crack index by more than 50%.



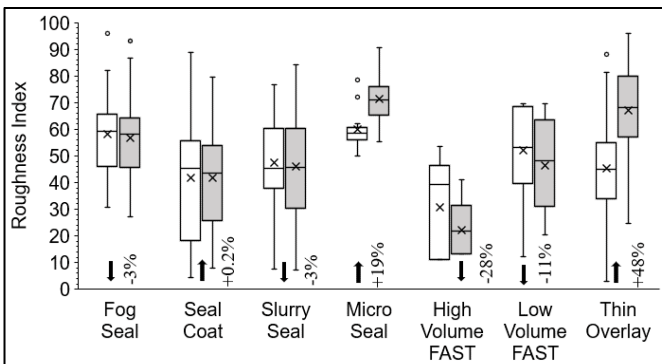
Main Distress/ Treatment Type	Transverse Crack Index		Difference in Transverse Crack Index
	Before Treatment	After Treatment	
Fog Seal	19	29	54%
Seal Coat	30	32	8%
Slurry Seal	15	76	402%
Micro Seal	12	56	367%
High Volume FAST	26	77	193%
Low Volume FAST	30	56	86%
Thin Overlay	22	88	305%

□ Transverse Crack Index Before Treatment
▩ Transverse Crack Index After Treatment
× Mean of Transverse Crack Index
∘ Outlier

Figure 7-6: A Comparison of Transverse Crack Index Before and After Treatment

7.3.2 Evaluation of Pavement Roughness after Preservation Treatment

Roughness index is derived from the IRI measured along the left and right wheel paths. As shown in Figure 7-7, roughness index improved after seal coat, micro seal, low volume FAST, and thin overlay treatments but lessened by 5% after slurry seal and high volume FAST. Irrespective of the treatment type, roughness index remains low. The highest roughness index observed was on micro seal treated pavement and had a roughness index of 71.



Main Distress/ Treatment Type	Roughness Index		Difference in Roughness Index
	Before Treatment	After Treatment	
Fog Seal	58	57	-3%
Seal Coat	42	42	0.2%
Slurry Seal	47	46	-3%
Micro Seal	60	71	19%
High Volume FAST	31	22	-28%
Low Volume FAST	52	47	-11%
Thin Overlay	45	67	48%

□ Roughness Index Before Treatment
▩ Roughness Index After Treatment
× Mean of Roughness Index
∘ Outlier

Figure 7-7: A Comparison of Roughness Index Before and After Treatment

The roughness indicator, MPD, was also evaluated, and Figure 6-2 shows a comparison of MPD before and after treatment. Depending on the pavement surface texture, MPD value ranges from 0.80 mm (0.0313 in) after thin overlay treatment to 2.43 mm (0.0958 in) after high volume FAST treatment. Pavement surface texture is influenced by the aggregate and binder composition.

Liquid Road, composed of small and large silica and limestone, and clay balls, is expected to replenish fine aggregates to the existing aged pavement and provide a smooth textured pavement surface. A double coat application of seal coat on rough pavement improves the pavement texture but does not fill the undulation in heavily pitted roads where MPD remains high. QS 68-18 is bounded by Opportunity Way to Anthem Way and 46th Lane to Vision Way. All streets in the quarter section received a double seal coat. MPD on Fortune Drive between 46th Lane and 45th Drive in QS 68-18 before treatment was 1.53 mm (0.0602 in) and after double seal coat was 1.33 mm (0.0523 in). Therefore, a double coat of Liquid Road on an existing pavement which has lost coarse aggregates and intermediate aggregates will not significantly improve pavement surface macrotexture as shown in Figure 6-5.

The QS 8-26 area bounded by I-17 (Maricopa Freeway) to Buckeye Road and 15th Avenue to 7th Avenue received Low Volume FAST and capped with a single coat application of Liquid Road on May 27, 2020. A field picture of a street in the QS 8-26 area is shown in Figure 7-8. MPD value measured on November 19, 2020, was 1.2 mm (0.0523 in), and pavement surface texture is not smooth enough for skating.

Figure 7-8: Low Volume FAST Capped with a Single Coating of Liquid Road Application

7.4 EVALUATING TREATMENT PERFORMANCE

7.4.1 Preservation Treatment Performance over Time

A complete review and validation of the pavement performance over time to validate the pavement performance model is not feasible with just two years of pavement condition data; thus, only an initial assessment of the pavement performance model was conducted for this study. The distresses observed in just a few months after preservation treatments, are the testament of the importance of the treatment. The performance models developed in Chapter 4 using the LTPP dataset show that the life extension for thin overlay is 9.7 years, 7.2 years for chip seals and 4.2 years for slurry seals using SCI. The life extension is slightly different for thin overlays using a different performance indicator. The life extension for thin overlay is 9.2 years, 7.2 years for chip seals and 4.2 years for slurry seals using PCI.

7.5 STRATEGIES TO ADDRESS PREVALENT DISTRESSES

7.5.1 Transverse Cracking

Cracking in asphalt may be induced by the traffic loading or environmental loading. The repetitive traffic loading is the major contributor causing fatigue cracking in the wheel path. On the other hand, daily or seasonal temperature cycling inducing tensile stress greater than tensile strength in asphalt pavement is the major contributor resulting in thermal fatigue cracking on the surface which eventually propagates down the pavement layer over time. Even at the stress level less than the tensile strength of material, repetitive daily temperature cycles eventually induce thermal fatigue cracking in the pavement (Vinson, Janoo, & Haas, 1989). Low temperature thermal cracking is widely recognized, and numerous researchers have been performed to tackle the issue. However thermal cracking occurring in a non-freeze area like Phoenix caused by a large temperature differential is one of the major asphalt pavement distresses that still need to be tackled at many levels.

According to Wikipedia, the City of Phoenix is located within the sunniest region in the world and averages 300 days or 3,872 hours of bright sunshine per year. It has a hot and desert like climate with long and extremely hot summers and short and mild to warm winters. A review of the historical temperature data for Phoenix downloaded from AccuWeather Inc. was performed.

The daily high and low temperature between January 1, 2017, and January 31, 2018, are tabulated in Appendix C. The average 7-day maximum air temperature of 47°C (116°F) was recorded in June. The maximum temperature of 48°C (119°F) was recorded on June 20, 2017, while the minimum temperature of 2°C (35°F) was recorded on January 28, 2017. 316 days out of 396 days (about 80% of the days in a 13-month study period), the Phoenix area experienced a temperature gradient of 11°C (20°F) in a twenty-four-hour period. The highest temperature difference of 19°C (35°F) (low of 23°C (73°F) and high of 42°C (108°F)) occurred once on the summer day, on June 15, 2017. The highest temperature difference of 19°C (35°F) (low of 7°C (45°F) and high of 26°C (80°F)) also occurred once in the winter on January 28, 2017.

Transverse cracks are observed in pavements with no pre-existing cracks or joints and may be the only type of distress observed on aged pavements. Figure 7-9 shows typical transverse cracking pavements in the City of Phoenix. A review of Phoenix temperature condition confirms that transverse cracks also referred to as thermal cracking in asphalt pavement observed in the City of Phoenix roadways most probably resulted from the shrinkage or contraction of the asphalt concrete surface. It is apparent that these transverse cracks are not load-related and are not reflection cracks. Shrinkage of the surface material is generally caused by oxidation and age hardening while contraction is caused by thermal fluctuations. Pavements in Phoenix aged noticeably faster due to the extreme heat and radiation from the sun. Transverse cracking usually occurs when the asphalt is exposed to cool or declining temperatures before it has completely hardened and while the hot asphalt mixture is still warm. As temperature decreases, the asphalt pavements begin to tighten and then contract and shrink, resulting in cracks in a pattern that is perpendicular or transverse to the pavement's centerline.

A review of the general soil maps prepared by the United States Department of Agriculture Soil Conservation Service (SCS) was performed and the soils at the locations where wide cracks are observed are tabulated in Appendix D. Soil type covering greater than 10% of the project locations are listed unless otherwise noted. Over the course of three years of field reviews, driven mostly by complaints from the residents, 70 locations with wide cracks, greater than 38 mm (1.5 in) were compiled. There were 49 out of 70 locations with more than 10% of their area covered with shrink and swell potential types of soil. Since no soil testing was performed specifically for this research, shrink and swell soil types covering less than 10% of the area and in close proximity to the area where wide cracks were observed were also considered. 7 additional locations were observed to be constructed on expansive soil. Another 8 out of 70 pavement sections with wide cracks were constructed on dusty or low strength soil. Only 6 out of 70 pavement sections with wide cracks were constructed on soils that were not rated or suitable to support road construction and traffic. Remarkably, 64 out of 70 locations that were observed to have wide cracks are in the area with potential subgrade soil issue.

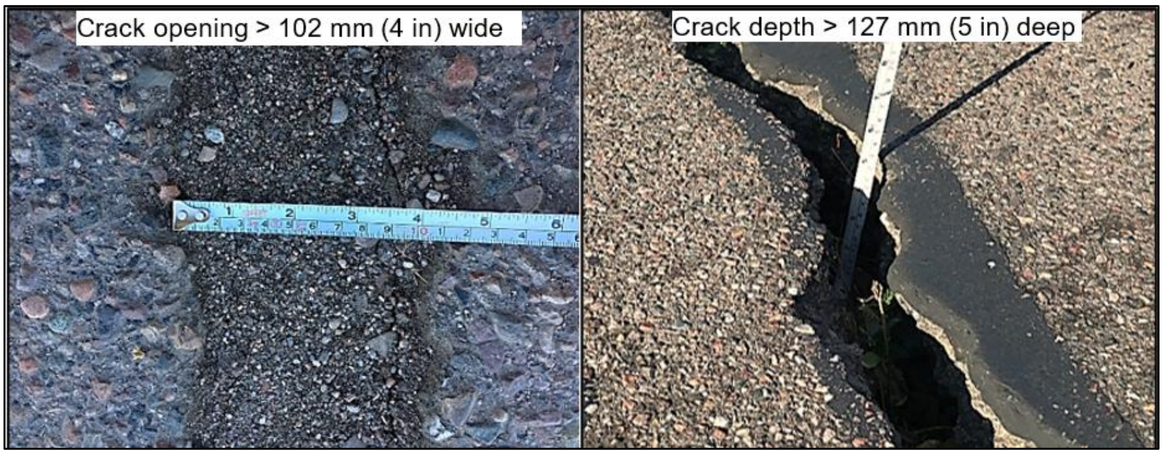


Figure 7-9: Transverse Cracking

Expansive soils are detrimental only if there is a change in moisture content, to cause either shrinking or swelling. The expansive soils swell by absorbing water when wetted and shrink when moisture is lost due to evaporation. Expansive soils around the world tend to have the same behaviors. Hot climatic regions tend to have dry expansive soils which tend to exhibit hydrophilic behavior. As the soils absorb more water their volume increases and an expansion of 10% is not uncommon (Chen, 1988) & (Nelson & Miller, 1992). The wetting and drying cycles that cause swelling and shrinking behavior resulting in undesirable volume changes can potentially cause significant damage to the flexible and rigid structures constructed over it.

Transverse cracks in the asphalt pavements are observed at a generally consistent range of crack-to-crack distance of 4.5 m (15 ft) to 27.5 m (90 ft). These cracks cause discomfort to the roadway users, potential damages to the vehicles, reduced safety for the traveling public, aesthetically unpleasant conditions, and progressive damages to the pavement structures and subgrades. Transverse asphalt cracking starts on the surface of the pavement and then gradually sinks deeper and deeper below the surface if they are not repaired immediately. Cracks less than 38 mm (1.5 in) can be sealed effectively with crack seals before they develop into wide cracks when crack sealants are no longer effective. The City has been working to find a solution to effectively seal wide cracks and to provide improved pavement conditions which will improve comfort and safety to the public and durability to the pavements. Full depth hot mix asphalt patching as well as a mixture of sand, cement, and water to fill the wide cracks had been attempted without success. Since the transverse cracks are widespread all along the lengths of the project roadway sections, it is very expensive and labor intensive to repair all individual cracks by saw-cutting the pavements for each transverse crack and patching. In addition, this type of repair will not solve the crack issue for too long since patches over time resulted in developing cracks on either side of the patches. However, if left unsealed, the sides of the wide crack are expected to become unstable due to subgrade damage caused by intrusion of water and repeated traffic loading.

One of the most significant factors to explore is the consistency characteristic of the bitumen used in the surface layer and the use of a softer asphalt binder is recommended to reduce or retard transverse crack (Yoder & Witczak, 1975). The consistency of an asphalt, a thermoplastic material, changes with temperature. A very important asphalt concrete property, temperature susceptibility, is defined as the rate at which the consistency of the asphalt changes with a change in temperature (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). The asphalt highly susceptible to the temperature change is not desirable because it can result in tender mix problems during compacting and at low temperature result in low temperature shrinkage cracking as it stiffens. The softer asphalt binder is described as asphalt exhibiting lower temperature susceptibility and/or better flow properties at lower temperature. As pavement ages, the asphalt material hardens and stiffens over time and makes material more susceptible to thermal cracking and increases the probability of obtaining a low critical temperature.

Based on numerous field and test section evaluations, a more severe transverse cracking was observed in asphalt pavement roads constructed in areas with sandy soil than on clay subgrades. It was also noted that increasing pavement thickness has no added benefit when asphalt pavement is already placed in an environmental condition susceptible to fracture. Attempts to address wide transverse cracks range from localized patching to major repair, rehabilitation, reconstruction, soil stabilization, and placement of moisture barrier. However, none of these methods make pavements less susceptible to the high temperature fluctuation to prevent thermal cracking and thereby waterproofing the pavement from water intrusion and preventing moisture migration to the expansive soil.

An ancillary laboratory study to manipulate and enhance the asphalt binder property to reduce thermal stress in the pavement and thereby mitigate one of the most critical distress, thermal cracking prevalent in areas prone to rapid temperature cycling was performed. For Phoenix area environmental conditions, PG 64-22 is selected as the control binder. “64” and “-22” represent the maximum and minimum pavement temperatures (deg C), respectively, which can be used at low traffic levels without likelihood of failure. PG 64-22 virgin binder, sourced from Phoenix, Arizona and supplied by Holly Frontier Corporation, was used for this ancillary laboratory study. A modified asphalt was prepared by adding 1 % of Aerogel by weight of the binder. Aerogel was selected for this study because it is a high-performance insulation material with extremely low density and has high thermal resistance properties. Enova Aerogel IC3110, a high-performance fine particle aerogel additive for insulative coatings manufactured by Cabot Aerogel, was used for this study. The original PG 64-22 was heated to 149°C (300°F) to soften and mix with the aerogel. Using the mechanical stirrer, the mixture was agitated for thirty minutes while the temperature controller was set to 356°F (180°C). It was noted that the required temperature was achieved only in the last few minutes. The aged binder to simulate the short-term aging which occurs during mixing, transport, and construction was prepared using the Rotating Thin Film Oven Test (RTFOT) method as specified by ASTM Designation D2872.

In the process to gain an insight into the modified asphalt binder, Brookfield viscosity test and Dynamic Shear Test (DSR) test were performed. In accordance with ASTM Designation

D4402/4402M, viscosity testing is performed on unaged asphalt binder samples to provide information on a fundamental property of an asphalt binder that is fairly repeatable. In accordance with ASTM Designation D7175, the test was performed to determine dynamic shear modulus and phase angle of the unaged control and modified asphalt binders and aged control binder.

Viscosity test is one of the approaches used in determining the temperature susceptibility of an asphalt binder. The test was performed at temperatures 121°C (250°F), 135°C (275°F), 149°C (300°F), 163°C (325°F), and 177°C (350°F) using Brookfield spindle number 27. Viscosity test yielding out of range torque readings below 10%, the rotational speed was raised or lowered to bring the torque to the specified range of 10% to 98%. For the control binder, since adjusting rotation speed still yielded torque lower than 10%, the spindle was changed from Brookfield spindle number 27 to 18. Although the relationship between viscosity and temperature is highly nonlinear, when "A-VTS" transformation is applied, a linear relationship does exist between viscosity and temperature. The mathematical expression, Equation 7-1, of this A-VTS relationship is captured by ASTM Ai-VTS equation:

$$log\, log(η) = A + VTS\, log(T_R) \qquad \text{Equation 7-1}$$

where

η = viscosity in centipoise;

A = regression parameter representing the intercept of temperature susceptibility relationship;

VTS = Viscosity Temperature Susceptibility (VTS), a regression parameter representing slope of temperature susceptibility; and

T_R= temperature in Rakhine.

The A and VTS parameters for the control binder sample tested using spindle number 18 (CTRL_S18) and 27 (CTRL_S27) and the modified binder with aerogel; for comparison, the parameters for different performance grade binders (PG 64-20 and PG 70-22) reported in the Mechanistic Empirical Pavement Design Guide (MEPDG) documentation are tabulated in Table 7-1 and are graphically represented in Figure 7-10.

Table 7-1: A and VTS Parameters for Sample Binders and MEPDG Binders

	PG 64-22 (MEPDG)	PG 70-22 (MEPDG)	CTRL_S27	CTRL_S18	Aerogel
Ai =	10.9800	10.2990	10.2140	10.1380	9.2353
VTSi =	-3.6800	-3.4260	-3.4165	-3.3915	-3.0656
R^2 =			1.0000	1.0000	0.9990

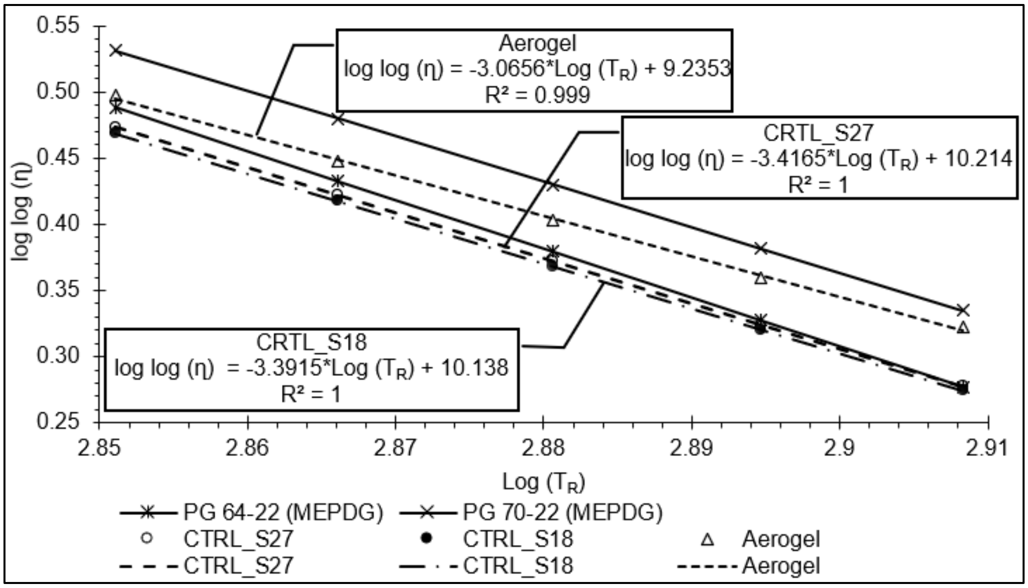


Figure 7-10: A-VTS Relation Plot

The viscosity increases as the PG grade goes up: the viscosity for PG 70-22 is higher than PG 64-22. The steeper slope represented by the larger VTS number indicates a higher temperature susceptibility. The modified binder with aerogel exhibited an improvement compared to the control binder and PG 64-22 MEPDG. Based on the A and VTS values obtained from the regression analysis, the modified binder has the lowest A and VTS values of 9.2353 and -3.0656 respectively. Thus, the PG 64-22 binder with aerogel is observed to be less susceptible to the temperature variation than the control binder.

The rheological properties of the unaged and aged control binder and unaged modified binder were measured at 58°C (136.4°F), 64°C (147°F), and 70°C (158°F) using 25 mm parallel plates with sinusoidal oscillatory load applied to the specimen at a frequency of 10.0 rad/s. As shown in Figure 7-11, the complex shear modulus (G*) value of the modified binder is higher than the unaged control binder but lower than the aged control binder, while the phase angle (δ) for the modified binder is lower than the unaged control binder but is higher than the aged control binder. The G*·sin δ, the fatigue cracking indicator, and G*/sin δ, the rutting indicator, for the modified binder, falls between the unaged and aged control binder as shown in Figure 7-12 and Figure 7-13. Therefore, the addition of aerogel does not significantly change the rheological properties of the original asphalt binder.

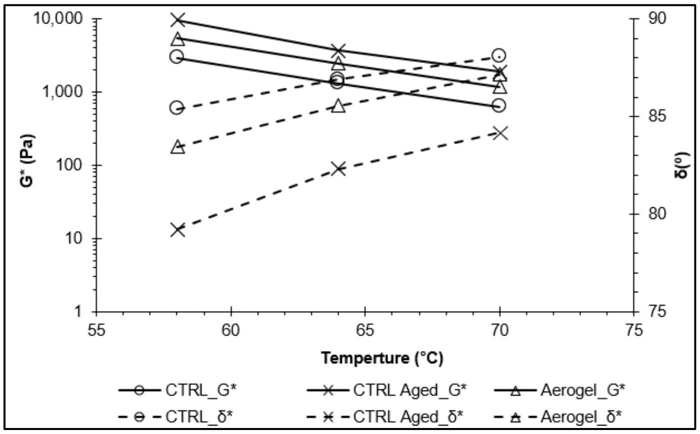


Figure 7-11: G* versus Temperature and δ versus Temperature Plot

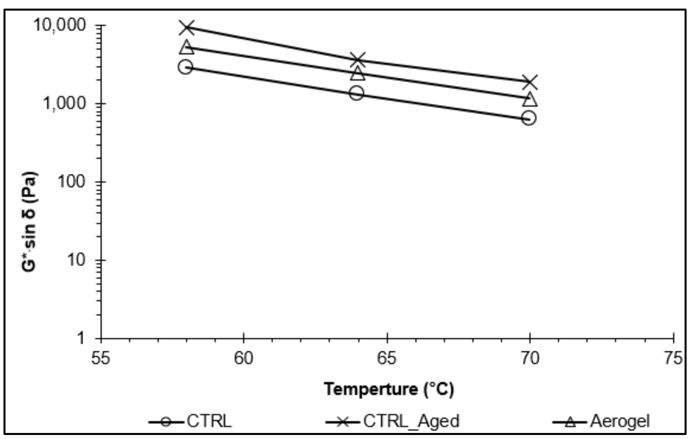


Figure 7-12: G*·sin δ Versus Temperature Plot

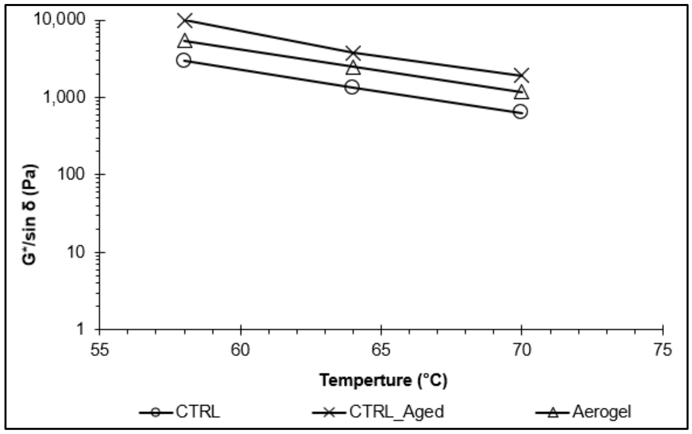


Figure 7-13: G*/sin δ Versus Temperature Plot

Based on this preliminary binder study, there is merit in investigating the use of modified binder to make the asphalt pavement less susceptible to temperature change.

In an attempt to mitigate the effect of heat from pavements in the urban environment, the City of Phoenix initiated a trial cool pavement program using CoolSeal. Pavements with CoolSeal applied to the surface were observed to have lower temperatures than pavements without CoolSeal. The highest temperature difference was 12°C (22°F) and the average temperature difference was 12°C (15°F). Therefore, to reduce the transverse cracking prevalent in the City of Phoenix, paving with a less temperature susceptible asphalt mix and/or applying cool surfacing products are recommended for further evaluation

7.5.2 Reflective Cracking

Reflective cracking occurs early in the service life of hot-mix asphalt overlays when placed over severely cracked pavements (Williams, Buss, & Chen, 2015). Because it is desirable to prevent reflective cracking to retain the structural integrity of the asphalt overlay, provide a watertight surface, and maintain a smooth ride quality, it is essential to understand the failure mechanism. An appropriate mitigation strategy can be developed once the failure mechanism is understood. The traffic and environmental loadings primarily cause reflective cracking to initiate either at the top or bottom of overlays (Von Quintus, Mallela, Weiss, Shen, & Lytton, 2009) and (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). The most common cause of the reflective cracking is due to the horizontal movement caused by temperature changes in flexible pavement layers. Due to the thermal expansion and contraction caused by temperature change, crack initiates in tension at the bottom of the overlay and propagates in tension and shear. Factors such as the magnitude and rate of temperature differential, distance between cracks, overlay properties influence the rate and extent of reflective cracking. The traffic induced reflective cracking is caused by the differential vertical deflection across the cracks in the existing pavement. The differential in vertical deflection can be caused by the reduction in the capability to transfer the traffic loading through the aggregate interlock across the crack interface. Factors such as the magnitude of the wheel load and transfer load influence reflective cracking.

There are treatments such as stress relieving interlayer used to retard the appearance of reflective cracking on existing HMA pavements as well as methods such as full depth reclamation (FDR) to completely remove the cracks that extend through all HMA layers. Reflective cracking as shown in Figure 7-14 are typically observed a few months after preservation treatments. Although these reflective cracks do not generally reduce the pavement structural capacity, moisture intrusion through cracks and the effects of the environmental and traffic loading can cause premature failure of the pavements. Therefore, the City of Phoenix has been investigating possible treatments to delay reflective cracking. In 1989, the city attempted pre-overlay repair of existing pavements in 20 quarter sections using geotextile fabrics. Since it was too cumbersome to lay the fabric, this method to control cracking was considered not feasible to proceed after the trial program.

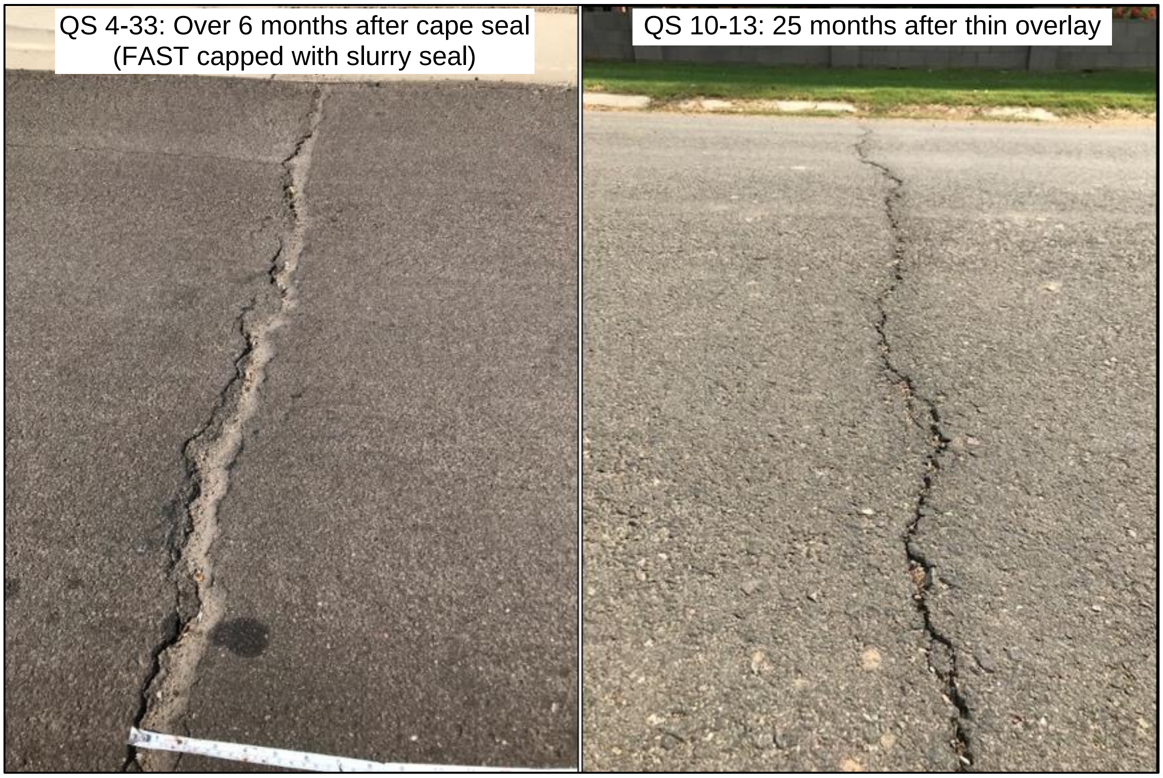


Figure 7-14: Reflection Cracking

The City of Phoenix's thin overlay mix has evolved over time and the chip seal is superseded by FAST. Recently, the city put forth several trial projects to mitigate pavement cracking. There were 13 thin overlay projects that received fog seals or CoolSeal that were reviewed as well. Reflective cracking was observed on these well-maintained pavements. The trial projects to reduce and delay reflective cracking involved FAST capped with seal coat or slurry seal/micro seal and pre-overlay treatment including scrub seal, FAST, RAP with rejuvenator, RAP chip seal, chip seal, RAP slurry seal, and Stress Absorption Membrane Interlayer (SAMI). In addition, fiber overlay and Ultra Thin Bonded Wearing Course (UTBWC) were evaluated. In-office review of ARAN crack maps when available and a field review of the pavements for the trial projects and several FAST and thin overlay projects were performed. The results from the reflective cracking investigation are tabulated in Appendix E. All the pavements are less than 5 years old and reflective cracks are observed, some more severe than others. As shown in Figure 7-15, the cracking observed was less severe in UTBWC and seen at the cul-de-sac area only. Since the majority of the UTBWC pavements are free of reflective cracking over 28 months after the application, it is the recommended treatment method to mitigate reflective cracking.

Figure 7-15: Pavement Condition Before, During, and After UTBWC Treatment in QS 30-20

During the field review, it was noticeable to observe the difference in pavement condition across a pavement section between thin overlay and edge milled and overlay section. As seen in Figure 7-16, the edge of the pavements which were milled to tie to the gutter flowline, which also removed the cracks from the existing pavement, were free of reflective cracks while block cracks were observed elsewhere. Therefore, milling to remove the cracks in the existing pavement is an effective strategy to control reflective cracking. However, the asphalt thickness on the local streets is only 50 mm (2 in) deep and milling is not possible without breaking the pavement. In such an instance, rubblization which is defined as the breaking of the existing pavement into sand size to 76 mm (3 in) pieces and overlaying with HMA may be a method to consider. Rubblization was observed to significantly retard the reflective cracking development in composite pavements compared to the mill and fill, overlay, and heater scarification (SCR) methods (Williams, Buss, & Chen, 2015).

Figure 7-16: Pavement Condition Before and After Thin Overlay on Rose Ln between Black Canyon Frwy (I-17) and 23rd Ave

7.5.3 Surface Texture

Two main surface texture issues prominent in the City of Phoenix street network are raveling and rough texture as shown in Figure 7-17 and 7-18. Raveling and rough texture involve the disintegration of pavement structure or individual components such as binder or fine aggregates. Raveling is the dislodging of aggregates initiating at the surface layer and progressing downward caused by the loss of bonding between the aggregate particle and the asphalt coating. Factors such as a thick coating of dust on the aggregate, loss of fines from the asphalt mix, and inadequate compaction weaken the bond between the aggregate and the asphalt film contribute to the wearing of the aggregate on the surface with traffic and dislodging of the aggregate from the asphalt mixture (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). Depending on the severity of raveling, preservation treatments such as seal coat, slurry seal, and thin overlay may be used to restore or retard raveled pavements. Seal coat works well to lock pavements that began to ravel. Instead of repairing raveled pavements, slurry seal has been observed to ravel at tight turns such as at cul-de-sac, driveways, intersections with small radii, and on-street parking. Where tight maneuver and high or heavy traffic loading is expected, skin patching is recommended. Keeping the existing pavement surface clean and dry prior to the application is mandatory to prevent scabbing or delamination and keeping the trash truck out of the treated pavements is mandatory for the slurry seal to set. Pavements which had raveled to the extent that the previous surface layer is exposed can only be treated with a thin overlay.

The raveling of the rubber overlay occurred approximately a year after construction in 2015. While raveling can occur very rapidly, the rough surface texture or pitting occurs gradually as asphalt pavement oxidizes and the shearing stresses between tire and pavement surface removes the aggregate particles. This surface wear is accelerated by the loose particles on the pavement surface. Therefore, regular sweeping of the pavement to keep it clean and rejuvenating the pavement to retard oxidation and thereby prevent pavements from exhibiting rough surface texture. Slurry seal or micro seal can replenish the aggregate loss in the rough and pitted pavement.

Figure 7-17: Raveling at Intersection

Figure 7-18: Rough Texture

7.6 SUMMARY OF FINDINGS AND CONCLUSIONS

This portion of the study evaluated the effectiveness of the pavement preservation treatments used in the City of Phoenix and presented major distresses affecting the effectiveness of the preservation treatments. The major findings from this research work are highlighted below:

1. Based on an initial comparison of fatigue crack index, longitudinal non-wheel path crack, longitudinal wheel path crack, and transverse crack, all pavement preservation treatment improves cracking indices.
2. The roughness index on the other hand remains low irrespective of the treatment type.
3. MPD is a measurable performance indicator and represents the pavement surface texture performance better than IRI in the urban street network.

4. MPD values for thin overlay, slurry seal, and micro seal are low and typically roughness is improved after treatment. However, FAST is rougher than pavement before FAST treatment. Therefore, on the residential street where skating and stroller use are expected FAST texture is too rough to accommodate skate and stroller use.
5. The effectiveness of the preservation treatments is reduced when the underlying pavement is in poor condition.
6. Transverse cracking is typical in the City of Phoenix street network because of the high temperature differential condition. Therefore, designing pavement to be less susceptible to temperature change is the recommended treatment to mitigate transverse cracking.
7. Aerogel modified asphalt binder is less susceptible to the temperature change while CoolSeal reduces the pavement surface temperature.
8. Since expansive soils are scattered all over Phoenix, keeping the pavements watertight is critical to deter pavements from developing wide cracks.
9. Thin overlay with and without pretreatment and FAST with and without capping do not retard reflective cracking.
10. Milling the existing pavement to remove the existing cracking is observed to remove reflective cracking.
11. Ultra Thin Bonded Wearing Course outperformed other treatments to mitigate reflective cracking.
    12. Depending on the severity of pavement surface texture issue, preservation treatments such as seal coat, slurry seal or micro seal, and thin overlay can mitigate raveling and rough texture prevalent in the City of Phoenix street network.

CHAPTER 8

SUMMARY, CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

8.1 SUMMARY

Since its conception in 2008, the City of Phoenix has not evaluated its pavement management system. The city uses PMS to maintain approximately 7,724 km (4,800 mi) of roadway network. The upgrade to ARAN 9000 that is equipped with a Laser Crack Measurement System (LCMS) and with added capabilities in 2017, highlighted the need to review PMS. With the added capabilities, fatigue cracking that was not detected before was rated. Other concerns included the low pavement condition index ratings for newly paved roads and the requirements for scheduled fog seal projects to be upgraded to a heavier treatment also motivated this research effort.

Therefore, the objectives of this research were: (1) to evaluate the effectiveness of the existing City of Phoenix PMS and (2) to recommend improvements to the existing PMS. The scope of work included: literature review to gain better understanding on current PMS practices; exploring and evaluating ARAN's pavement condition data collection technology; select distresses to represent pavement surface condition prevalent in the City of Phoenix; analysis of deduct values, individual distress index, and pavement condition index; recommendation of treatment triggers for preservation treatments; development and validation of pavement performance models; evaluation and validation of PMS treatment recommendation with field assessed treatment recommendation; and conducting statistical analysis to evaluate the effectiveness of the PMS.

8.2 CONCLUSIONS

8.2.1 Literature Review

A literature review exploring the pavement management system and pavement surface roughness was conducted. Based on the literature review conducted, there were two main pavement preservation concepts missing. First, the pavement condition to perform the network level PMS for the preservation program is no different from the PMS for the maintenance, rehabilitation, and reconstruction. Since pavements that are in a structurally sound condition are good candidates for preservation treatment, a simple, possibly a single, performance measure to represent the overall condition of the pavement may be viable. This will allow agencies to be more flexible with their preservation treatments and minimize the pavement performance modeling effort. Secondly, the pavement surface texture roughness indicator to measure the performance of pavement surface texture deficiency was missing. Agencies had been using IRI to capture pavement roughness. However, pavement preservation treatment is not intended to correct the roadway profile which is captured by the IRI. Therefore, a performance indicator to capture pavement surface texture roughness is necessary for triggering preservation treatment.

8.2.2 City of Phoenix Pavement Preservation Program

The major findings from an evaluation of the City of Phoenix's non-technical and technical components of the pavement preservation program are highlighted below:

1. Overall, the city has a strong partnership with its street transportation stakeholders.
2. The efforts to collaborate with different departments and divisions can be improved by having pertinent data such as traffic count and maintenance and construction history be in sync with the PMS database rather than holding meetings to collect data.
3. The staffing of the pavement management team is lacking since the street network is very large and there is only one dedicated person to process and review pavement condition data.
4. Currently the city does not collect or use factors such as traffic and drainage and soil conditions that impact the pavement performance in PMS analysis.
5. Many private companies, departments, and divisions work in the street right of way, but only maintenance activities performed by the pavement maintenance sections are updated annually.
6. Pavement conditions in the urban network which is still growing and developing varies greatly, thus regrouping and redefining the pavement inventory sections was performed to avoid leaving out any untreated sections.
7. The upgrade to the new ARAN 9000 equipped with LCMS has a lot more capabilities than its predecessor.

8. Since LCMS is Pavemetric's proprietary technology, it was not possible to define the fatigue crack severity by the traditional method nor to differentiate fatigue cracking from block cracking.
9. FAST that is not raveled is rated as severely raveled by LCMS. Thus, mean profile depth is proposed as a performance indicator to measure pavement surface texture condition.

8.2.3 Simplified Pavement Assessment Method for Preservation Program

An investigation of pavement performance measures: surface cracking, surface texture, and surface deformation to represent the overall pavement condition was performed. The ASTM method of pavement performance measure, PCI, was compared to the developed and proposed performance measure, SCI; and the optimal timing and triggers to select preservation treatments based on surface cracking were established. Findings were as follows:

1. Pavement surface cracking index SCI is strongly correlated to the pavement condition index for the PCI range above 70.
2. SCI can be used as a pavement performance indicator to perform PMS analysis for the preservation program.
3. Based on both the PCI and SCI performance curves developed in this study, the expected life extension, and the rate of deterioration for original hot-mix dense graded asphalt pavements with no maintenance, hot-mix dense graded thin overlay, chip seal, and slurry seal are different and overlay outperformed others.
4. Performance of preservation treatment is affected by the pretreatment pavement condition, environment, traffic loading, and construction and material quality. Preservation treatments such as thin overlays, chip seals, and slurry seals were the three primarily investigated.
5. Based on the SCI analysis, a preservation treatment decision tree was developed to incorporate into the preservation treatment program and or PMS. The threshold to trigger overlay treatment is when SCI is greater than 70 with a max low severity fatigue cracking limit of 11%; chip seal is when SCI is greater than 75 with a max low severity fatigue

cracking limit of 6%; slurry seal is when SCI is greater than 80 with max low severity fatigue cracking limit of 1%; and fog seal is when SCI is greater than 90.

8.2.4 Validation of the City of Phoenix Condition Assessment Method

The major findings from the validation of the City of Phoenix's pavement condition assessment method and the comparison of various manual and automated survey methods are highlighted below:

1. The difference in the survey procedures, automated versus manual survey methods or surveying multiple sample survey inventory areas versus the whole length of the section, can result in a large difference in PCI.
2. The City of Phoenix PCI is much lower than PCI determined using RoadBotics and PCI or SCI determined from manual survey methods.
3. The City of Phoenix method of pavement condition assessment is weakly correlated with manual survey pavement assessment methods as well as the RoadBotics method.
4. Since the actual field treatment recommendation considers factors such as maintenance history and future construction activities, beyond the pavement condition, the PMS analysis can only be used as a tool to assist, not make the final decision, in recommending the specific preservation treatment.

8.2.5 Macrotexture Index

This part of the study investigated pavement surface macrotexture characteristics, developing surface macrotexture performance models for hot-mix dense graded overlay and chip seal, and establishing thresholds to trigger surface texture treatments. Major findings were:

1. Pavement surface macrotexture for various pavement surface types was different: macrotexture depth for fiber slurry seal was the lowest with MPD of 0.61 mm and the highest with MPD of 2.97 mm for the pitted and rough textured pavement.
2. Pavement surface macrotexture indicators, MTD, measured using the manual method, and MPD, measured using the automated method, were strongly correlated.
3. An analysis of before and after preservation treatments demonstrated a 37% reduction in MPD for slurry seal and 63% increase in MPD after FAST.

4. In an approximately two-year period, an increase in MPD for a raveled pavement was 23% and was less than 1% for the fatigue pavement. The increase in MPD for a pitted pavement which had already lost binder and fine aggregate was about 5%.
5. Based on a review of the pavement surface macrotexture performance after an overlay, during the first 18 months, pavement surface texture may go through a rapid increase and rapid decrease in macrotexture depth due to the traffic, aggregate gradation, asphalt type, and mixture composition.
6. The pavement surface macrotexture performance models developed from the historical MPD data from LTPP database showed a gradual increase in MPD over time for a hot-mix dense graded asphalt overlay and a gradual decrease in MPD over time for chip seals.
7. The rate of change of MPD, derived from the MPD performance model, can be used to objectively rate raveling and bleeding.
8. Since pavement surface macrotexture greater than MPD of 1.2 mm measured using LCMS is rougher than slurry seal surface, MPD greater than 1.2 mm is defined as a rough pavement surface texture that may or may not be raveled.
9. Based on pavement surface macrotexture performance measures, a preservation treatment decision tree to address pavement surface texture issues can be developed and incorporated into the preservation treatment program.

8.2.6 Effectiveness of Pavement Preservation Treatments

The major findings from the evaluation of the effectiveness of the pavement preservation and the investigation of predominant distresses affecting the preservation treatment performance are highlighted below:

1. Based on an initial comparison of fatigue crack index, longitudinal non-wheel path crack, longitudinal wheel path crack, and transverse crack, all pavement preservation treatment improves cracking indices.
2. The roughness index on the other hand remains low irrespective of the treatment type.

3. MPD is a measurable performance indicator and represents the pavement surface texture performance better than IRI in the urban street network.
4. MPD values for thin overlay, slurry seal, and micro seal are low and typically roughness is improved after treatment. However, FAST is rougher than pavement before FAST treatment. Therefore, on the residential street where skating and stroller use are expected FAST texture is too rough to accommodate skate and stroller use.
5. The effectiveness of the preservation treatments is reduced when the underlying pavement is in poor condition.
6. Transverse cracking is typical in the City of Phoenix street network because of the high temperature differential condition. Therefore, designing pavement to be less susceptible to temperature change is the recommended treatment to mitigate transverse cracking.
7. Aerogel modified asphalt binder is less susceptible to the temperature change while CoolSeal reduces the pavement surface temperature.
8. Since expansive soils are scattered all over Phoenix, keeping the pavements watertight is critical to deter pavements from developing wide cracks.
9. Thin overlay with and without pretreatment and FAST with and without capping do not retard reflective cracking.

8.3 RECOMMENDATIONS AND FUTURE WORK

With the acquisition of the new pavement assessment technology, an evaluation of PMS is required. Due to the data availability, the scope of this study was limited. After the pavement condition data has been collected for at least three data collection years, the pavement performance of the pavement with and without the treatments needs to be evaluated. A range of pavement conditions between 0 and 100 will have to be reviewed in the field and so deduct values to rate the pavement condition can be calibrated. The pavement condition performance model will have to be developed and the treatment decision matrix need to be updated so PMS analysis can be performed accurately, and pavement deterioration rate can be properly predicted. The reset values after each specific treatment can be updated after sufficient historical data is available to determine the long-term treatment benefit.

The pavement surface macrotexture measure is a very promising performance indicator that can be used to enhance the pavement preservation treatment strategy. Since the pavement macrotexture is dependent on asphalt pavement mix design and construction method, establishing an initial pavement macrotexture depth for each preservation treatment type will allow an agency to set a specification as well as allow an agency to determine the rate of change of texture at an early stage. Since the long-term pavement macrotexture performance information is still very limited, additional research exploring the factors affecting the pavement macrotexture will be beneficial.

This research study evaluated the effect of the pretreatment condition on the pavement performance after treatment for slurry seal, chip seal, and overlay. There are other preservation treatments such as micro seal and cape seal that are worth investigating. Moreover, exploring the influence of traffic, overlay thickness, subgrade condition, material and construction quality, and many other factors to extend the life of the preservation treatments will also be of value to the agencies.

The pavement performance models, and the treatment decision trees developed as part of this research study using LTPP need to be verified with field data. After sufficient data is available, the SCI and pavement surface macrotexture performance model may be developed for the City of Phoenix and verified using historical data. The performance model developed from LTPP can only be used as a guide in developing models reflecting the City of Phoenix pavement condition and performance.

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APPENDIX A

FIELD REEVALUATION OF 2021 FOG SEAL PROGRAM

No.	Street Or Quarter Section	From	To	2021 Programmed Treatment	Field Recommended Treatment	Reasons for Recommending Treatment Upgrade
1.	QS 012-22	Pecos Rd / Shaughnessey Rd	31st Ave / Chandler Blvd	Fog Seal	Fog Seal	N/A
2.	QS 012-28	Pecos Rd / Frye Rd	2nd Pl / Desert Foothills Prkwy	Fog Seal	Fog Seal	N/A
3.	QS 012-30	Liberty Ln / Glenhaven Dr	12th St / 14th St	Fog Seal	Fog Seal	N/A
4.	QS 012-32	Pecos Rd / Liberty Ln	18th Wy / 24th St	Fog Seal	Fog Seal	N/A
5.	QS 01-25	South Mountain Ave / Baseline Rd	19th Ave / 15th Ave	Fog Seal	Fog Seal	N/A
6.	QS 01-31	South Mountain Ave / Baseline Rd	16th St / 20th St	Fog Seal	Fog Seal	N/A
7.	QS 1-16 & QS 2-16	Baseline Rd / Southern Ave	55th Ave / 51st Ave	Fog Seal	Fog Seal	N/A
8.	QS 12-32	Rosevelt St / Mcdowell Rd	20th St / 24th St	Fog Seal	Fog Seal	N/A
9.	QS 17-16	Glenrosa Ave / Campbell Ave	55th Ave / Maryvale Pkwy	Fog Seal	Fog Seal	N/A
10.	QS 18-1 & QS 18-2	Campbell Ave / Camelback Rd	113rd Dr / 107th Ave	Fog Seal	Fog Seal	N/A
11.	QS 34-33	Acoma Dr / Greenway Rd	Cave Creek Rd / 27th St	Fog Seal	Fog Seal	N/A
12.	QS 57-23 & QS 58-23	Dove Valley Rd / Carefree Hwy	27th Dr / 21st Dr	Fog Seal	Fog Seal	N/A
13.	QS 6-37	Elwood St / University Dr	40th St / 44th St	Fog Seal	Fog Seal	N/A
14.	QS 7-3 & QS 8-3	Lower Buckeye Rd / Buckeye Rd	107th Ave / 103rd Ave	Fog Seal	Fog Seal	N/A

No.	Street Or Quarter Section	From	To	2021 Programmed Treatment	Field Recommended Treatment	Reasons for Recommending Treatment Upgrade
15.	QS 9-29	Buckeye Rd / Union Pacific Railroad	7th St / 12th St	Fog Seal	Fog Seal	N/A
16.	QS 9-30	Buckeye Rd / Union Pacific Railroad	12th St / 16th St	Fog Seal	Fog Seal	N/A
17.	12th St	Camelback Rd	Bethany Home Rd	Fog Seal	Fog Seal	N/A
18.	12th St	Campell Ave	Camelback Rd	Fog Seal	Fog Seal	N/A
19.	23rd Ave	Pinnacle Peak Rd	Happy Valley Rd	Fog Seal	Fog Seal	N/A
20.	24th St	Jefferson St	Van Buren St	Fog Seal	Fog Seal	N/A
21.	24th St	Pecos Rd	Chandler Blvd	Fog Seal	Fog Seal	N/A
22.	32nd St	Piestewa Frwy (SR 51)	Shea Blvd	Fog Seal	Fog Seal	N/A
23.	35th Ave	Bell Rd	Union Hills Dr	Fog Seal	Fog Seal	N/A
24.	35th Ave	Deer Valley Rd	Pinnacle Peak Rd	Fog Seal	Fog Seal	N/A
25.	40th St	Thomas Rd	Indian School Rd	Fog Seal	Fog Seal	N/A
26.	67th Ave	Campbell Ave	Camelback Rd	Fog Seal	Fog Seal	N/A
27.	7th Ave	Maricopa Frwy (I-17)	Buckeye Rd	Fog Seal	Fog Seal	N/A
28.	7th St	Coral Gables Dr	Greenway Pkwy	Fog Seal	Fog Seal	N/A
29.	83rd Ave	Broadway Rd	Elwood St	Fog Seal	Fog Seal	N/A
30.	99th Ave	Mobile Ln (City of Phoenix Boundary)	Broadway Rd	Fog Seal	Fog Seal	N/A
31.	Bell Rd	Cave Creek Rd	32nd St	Fog Seal	Fog Seal	N/A

No.	Street Or Quarter Section	From	To	2021 Programmed Treatment	Field Recommended Treatment	Reasons for Recommending Treatment Upgrade
32.	Buckeye Rd	Black Canyon Frwy (I-17)	19th Ave	Fog Seal	Fog Seal	N/A
33.	Camelback Rd	107th Ave	99th Ave	Fog Seal	Fog Seal	N/A
34.	Camelback Rd	19th Ave	7th Ave	Fog Seal	Fog Seal	N/A
35.	Central Ave	Indian School Rd	Camelback Rd	Fog Seal	Fog Seal	N/A
36.	Central Ave	Thomas Rd	Indian School Rd	Fog Seal	Fog Seal	N/A
37.	Deer Valley Rd	Black Mountain Blvd / 36th St	40th St	Fog Seal	Fog Seal	N/A
38.	Dobbins Rd	59th Ave	55th Ave	Fog Seal	Fog Seal	N/A
39.	Dove Valley Rd	North Valley Pkwy	22nd Ave	Fog Seal	Fog Seal	N/A
40.	Jefferson St	20th St	26th St	Fog Seal	Fog Seal	N/A
41.	Lower Buckeye Rd	51st Ave	35th Ave	Fog Seal	Fog Seal	N/A
42.	Lower Buckeye Rd	91st Ave	83rd Ave	Fog Seal	Fog Seal	N/A
43.	Mayo Blvd	End Of Road	Tatum Blvd	Fog Seal	Fog Seal	N/A
44.	Mcdowell Rd	83rd Ave	75th Ave	Fog Seal	Fog Seal	N/A
45.	New River Rd	Mile Marker 4	Mile Marker 5	Fog Seal	Fog Seal	N/A
46.	New River Rd	Mile Marker 9	Phoenix Sign / Cattle Guard	Fog Seal	Fog Seal	N/A
47.	North Valley Pkwy	Dove Valley Rd	End Of Road	Fog Seal	Fog Seal	N/A
48.	Paloma Pkwy	Sonoran Blvd	Dove Valley Rd	Fog Seal	Fog Seal	N/A
49.	Peoria Ave	43rd Ave	35th Ave	Fog Seal	Fog Seal	N/A
50.	Pinnacle Vista Dr	Inspiration Mountain Pkwy	Pyramid Peak Pkwy	Fog Seal	Fog Seal	N/A

No.	Street Or Quarter Section	From	To	2021 Programmed Treatment	Field Recommended Treatment	Reasons for Recommending Treatment Upgrade
51.	QS 011-36	Frye Rd / Chandler Blvd	35th Wy / 40th St	Fog Seal	Slurry Seal	Localized fatigue cracking, slurry seal raveling
52.	QS 27-31 & QS 28-31	Dunlap Ave / Cheryl Dr	16th St / 20th St	Fog Seal	Slurry Seal	Block cracking, raveling, patching required to repair localized poor pavement condition
53.	QS 29-21	Peoria Ave / Cholla St	35th Ave / 31st Ave	Fog Seal	Slurry Seal	Block cracking, raveling
54.	QS 31-23	Cactus Rd / Thunderbird Rd	Black Canyon Frwy (I-17) / 25th Ave	Fog Seal	Slurry Seal	Localized fatigue cracking, raveling, block cracking
55.	35th Ave	Alameda Rd	Hackamore Dr	Fog Seal	Micro Seal	Rough surface texture
56.	35th Ave	Agua Fria Frwy (SR 101)	Deer Valley Rd	Fog Seal	Micro Seal	Localized fatigue cracking, rough surface texture
57.	40th St	End Of Road	Deer Valley Rd	Fog Seal	Micro Seal	Localized fatigue cracking
58.	43rd Ave	Anthem Wy	End Of Road	Fog Seal	Micro Seal	Rough surface texture
59.	51st Ave	Lower Buckeye Rd	Buckeye Rd	Fog Seal	Micro Seal	Rough surface texture
60.	56th St	Indian School Rd	Camelback Rd	Fog Seal	Micro Seal	Localized fatigue cracking, block cracking, rough surface texture
61.	56th St	Thomas Rd	Indian School Rd	Fog Seal	Micro Seal	Localized fatigue cracking, localized raveling, block cracking, rough surface texture
62.	67th Ave	Buckeye Rd	Van Buren St	Fog Seal	Micro Seal	Localized fatigue cracking, localized raveling, rough surface texture
63.	75th Ave	Baseline Rd	City of Phoenix Bundary	Fog Seal	Micro Seal	Rough surface texture
64.	75th Ave	Buckeye Rd	Van Buren St	Fog Seal	Micro Seal	Localized fatigue cracking
65.	99th Ave	Broadway Rd	Lower Buckeye Rd	Fog Seal	Micro Seal	Rough surface texture

No.	Street Or Quarter Section	From	To	2021 Programmed Treatment	Field Recommended Treatment	Reasons for Recommending Treatment Upgrade
66.	Elliot Rd / Warner Rd	Equestrian Tr	44nd St	Fog Seal	Micro Seal	Localized fatigue cracking, block cracking
67.	Lone Mountain Rd	40th St	Cave Creek Rd	Fog Seal	Micro Seal	Localized fatigue cracking, block cracking, potholes
68.	Paradise Village Pkwy	Tatum Blvd	Tatum Blvd	Fog Seal	Micro Seal	Raveling, block cracking, rough surface texture
69.	Southern Ave	35th Ave	27th Ave	Fog Seal	Micro Seal	Localized fatigue cracking, localized raveling
70.	Warner Rd	Equestrian Tr	48th St	Fog Seal	Micro Seal	Localized fatigue cracking, block cracking
71.	QS 33-35	Thunderbird Rd / Hearn Rd	32nd St / 36th St	Fog Seal	FAST	Fatigue cracking, block cracking, rough surface texture, raveling
72.	QS 011-31	Clubhouse Dr / Chandler Blvd	Marketplace Wy / 24th St	Fog Seal	Thin Overlay	Fatigue cracking
73.	QS 14-26	Encanto Blvd / Thomas Rd	15th Ave / 7th Ave	Fog Seal	Thin Overlay	Fatigue cracking, raveling, block cracking
74.	12th St	Osborn Rd	Indian School Rd	Fog Seal	Thin Overlay	Fatigue cracking, block cracking, rough surface texture, potholes
75.	16th St	Baseline Rd	Southern Ave	Fog Seal	Thin Overlay	Localized fatigue cracking, localized shoving at an intersection, localized scabbing
76.	43rd Ave	Northern Ave	Dunlap Ave	Fog Seal	Thin Overlay	Fatigue cracking, block cracking
77.	Central Ave	Bethany Home Rd	Glendale Ave	Fog Seal	Thin Overlay	Fatigue cracking, block cracking
78.	Deer Valley Rd	7th St	16th St	Fog Seal	Thin Overlay	Fatigue cracking, rough surface texture, potholes
79.	Pathfinder Dr / Marriot Dr	Tatum Blvd	Deer Valley Rd	Fog Seal	Thin Overlay	Fatigue cracking, raveling

APPENDIX B

A COMPARISON OF FIELD VS. PMS ANALYSIS TREATMENT RECOMMENDATIONS

Arterial and Collector Street Sub-Network

No.	Super Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
1.	SS005690	Fog Seal	Fog Seal	Same
2.	SS016340	Fog Seal	Fog Seal	Same
3.	SS035920	Fog Seal	Fog Seal	Same
4.	SS036820	Fog Seal	Fog Seal	Same
5.	SS037780	Fog Seal	Fog Seal	Same
6.	SS007290	Fog Seal	Fog Seal	Same
7.	SS021400	Fog Seal	Fog Seal	Same
8.	SS025565	Micro Seal	Micro Seal	Same
9.	SS013490	Micro Seal	Micro Seal	Same
10.	SS017010	Micro Seal	Micro Seal	Same
11.	SS018680	Thin Overlay	Thin Overlay	Same
12.	SS032450	Thin Overlay	Thin Overlay	Same
13.	SS039340	Thin Overlay	Thin Overlay	Same
14.	SS032400	Thin Overlay	Thin Overlay	Same
15.	SS018420	Thin Overlay	Thin Overlay	Same
16.	SS016850	Thin Overlay	Thin Overlay	Same
17.	SS018335	Thin Overlay	Thin Overlay	Same
18.	SS018430	Thin Overlay	Thin Overlay	Same
19.	SS030110	Thin Overlay	Thin Overlay	Same
20.	SS039350	Thin Overlay	Thin Overlay	Same
21.	SS020220	Thin Overlay	Thin Overlay	Same
22.	SS038760	Thin Overlay	Thin Overlay	Same
23.	SS038770	Thin Overlay	Thin Overlay	Same
24.	SS038780	Thin Overlay	Thin Overlay	Same
25.	SS022950	Thin Overlay	Thin Overlay	Same
26.	SS041580	Thin Overlay	Thin Overlay	Same
27.	SS039380	Thin Overlay	Thin Overlay	Same
28.	SS037300	Thin Overlay	Thin Overlay	Same
29.	SS022160	Thin Overlay	Thin Overlay	Same
30.	SS037800	Thin Overlay	Thin Overlay	Same
31.	SS021380	Micro Seal	Fog Seal	Downgraded Treatment
32.	SS043390	Micro Seal	Fog Seal	Downgraded Treatment
33.	SS010720	Micro Seal	Fog Seal	Downgraded Treatment
34.	SS046650	Thin Overlay	Fog Seal	Downgraded Treatment
35.	SS015750	Thin Overlay	Fog Seal	Downgraded Treatment
36.	SS026350	Thin Overlay	Fog Seal	Downgraded Treatment
37.	SS032430	Thin Overlay	Fog Seal	Downgraded Treatment
38.	SS032440	Thin Overlay	Fog Seal	Downgraded Treatment
39.	SS032795	Thin Overlay	Fog Seal	Downgraded Treatment
40.	SS037440	Thin Overlay	Fog Seal	Downgraded Treatment
41.	SS037790	Thin Overlay	Fog Seal	Downgraded Treatment
42.	SS038390	Thin Overlay	Fog Seal	Downgraded Treatment
43.	SS041600	Thin Overlay	Fog Seal	Downgraded Treatment

No.	Super Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
44.	SS039400	Thin Overlay	Fog Seal	Downgraded Treatment
45.	SS038460	Thin Overlay	Micro Seal	Downgraded Treatment
46.	SS016975	Thin Overlay	Micro Seal	Downgraded Treatment
47.	SS032160	Thin Overlay	Micro Seal	Downgraded Treatment
48.	SS017320	Thin Overlay	Micro Seal	Downgraded Treatment
49.	SS011490	Thin Overlay	Micro Seal	Downgraded Treatment
50.	SS032360	Thin Overlay	Micro Seal	Downgraded Treatment
51.	SS033300	Thin Overlay	Micro Seal	Downgraded Treatment
52.	SS033330	Thin Overlay	Micro Seal	Downgraded Treatment
53.	SS020060	Thin Overlay	Micro Seal	Downgraded Treatment
54.	SS016995	Thin Overlay	Micro Seal	Downgraded Treatment
55.	SS049250	Thin Overlay	Micro Seal	Downgraded Treatment
56.	SS012200	Thin Overlay	Micro Seal	Downgraded Treatment
57.	SS035290	Thin Overlay	Micro Seal	Downgraded Treatment
58.	SS037840	Thin Overlay	Micro Seal	Downgraded Treatment
59.	SS037850	Thin Overlay	Micro Seal	Downgraded Treatment
60.	SS034310	Thin Overlay	Micro Seal	Downgraded Treatment
61.	SS037220	Fog Seal	Micro Seal	Upgraded Treatment
62.	SS024930	Fog Seal	Micro Seal	Upgraded Treatment
63.	SS040450	Fog Seal	Micro Seal	Upgraded Treatment
64.	SS047400	Fog Seal	Micro Seal	Upgraded Treatment
65.	SS040410	Fog Seal	Micro Seal	Upgraded Treatment
66.	SS026290	Fog Seal	Micro Seal	Upgraded Treatment
67.	SS006220	Fog Seal	Thin Overlay	Upgraded Treatment
68.	SS027670	Fog Seal	Thin Overlay	Upgraded Treatment
69.	SS023190	Fog Seal	Thin Overlay	Upgraded Treatment
70.	SS030970	Micro Seal	FAST	Upgraded Treatment
71.	SS045180	Micro Seal	FAST	Upgraded Treatment
72.	SS008210	Micro Seal	FAST	Upgraded Treatment
73.	SS023820	Micro Seal	Thin Overlay	Upgraded Treatment
74.	SS037030	Micro Seal	Thin Overlay	Upgraded Treatment
75.	SS034180	Micro Seal	Thin Overlay	Upgraded Treatment
76.	SS020780	Micro Seal	Thin Overlay	Upgraded Treatment
77.	SS019010	Micro Seal	Thin Overlay	Upgraded Treatment
78.	SS044550	Micro Seal	Thin Overlay	Upgraded Treatment
79.	SS018600	Micro Seal	Thin Overlay	Upgraded Treatment
80.	SS031720	Micro Seal	Thin Overlay	Upgraded Treatment
81.	SS030640	Micro Seal	Thin Overlay	Upgraded Treatment
82.	SS025270	Micro Seal	Thin Overlay	Upgraded Treatment
83.	SS005060	Micro Seal	Thin Overlay	Upgraded Treatment
84.	SS033170	Micro Seal	Thin Overlay	Upgraded Treatment

Local and Minor Collector Street Sub-Network

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
1.	QS5-28	FAST	FAST	Same
2.	QS9-26	FAST	FAST	Same
3.	QS42-26	FAST	FAST	Same
4.	QS43-23	FAST	FAST	Same
5.	QS43-24	FAST	FAST	Same
6.	QS44-25	FAST	FAST	Same
7.	QS9-13	FAST	FAST	Same
8.	SS014470	Fog Seal	Fog Seal	Same
9.	SS012930	Fog Seal	Fog Seal	Same
10.	SS023520	Fog Seal	Fog Seal	Same
11.	SS006330	Fog Seal	Fog Seal	Same
12.	SS030120	Fog Seal	Fog Seal	Same
13.	SS025450	Fog Seal	Fog Seal	Same
14.	SS039230	Fog Seal	Fog Seal	Same
15.	SS039490	Fog Seal	Fog Seal	Same
16.	SS023890	Fog Seal	Fog Seal	Same
17.	QS32-27	Fog Seal	Fog Seal	Same
18.	QS01-19	Fog Seal	Fog Seal	Same
19.	QS02-31	Fog Seal	Fog Seal	Same
20.	QS3-32	Fog Seal	Fog Seal	Same
21.	QS35-41	Fog Seal	Fog Seal	Same
22.	QS36-38	Fog Seal	Fog Seal	Same
23.	QS44-31	Fog Seal	Fog Seal	Same
24.	QS36-35	Fog Seal	Fog Seal	Same
25.	SS016000	Slurry Seal	Slurry Seal	Same
26.	SS020470	Slurry Seal	Slurry Seal	Same
27.	SS014800	Slurry Seal	Slurry Seal	Same
28.	SS014460	Slurry Seal	Slurry Seal	Same
29.	SS021160	Slurry Seal	Slurry Seal	Same
30.	SS012990	Slurry Seal	Slurry Seal	Same
31.	SS013190	Slurry Seal	Slurry Seal	Same
32.	SS011550	Slurry Seal	Slurry Seal	Same
33.	SS011740	Slurry Seal	Slurry Seal	Same
34.	SS011570	Slurry Seal	Slurry Seal	Same
35.	SS022260	Slurry Seal	Slurry Seal	Same
36.	SS010660	Slurry Seal	Slurry Seal	Same
37.	SS022610	Slurry Seal	Slurry Seal	Same
38.	SS026400	Slurry Seal	Slurry Seal	Same
39.	SS023950	Slurry Seal	Slurry Seal	Same
40.	SS007930	Slurry Seal	Slurry Seal	Same
41.	SS006500	Slurry Seal	Slurry Seal	Same

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
42.	SS006490	Slurry Seal	Slurry Seal	Same
43.	SS039970	Slurry Seal	Slurry Seal	Same
44.	SS040020	Slurry Seal	Slurry Seal	Same
45.	SS038540	Slurry Seal	Slurry Seal	Same
46.	SS036660	Slurry Seal	Slurry Seal	Same
47.	SS036640	Slurry Seal	Slurry Seal	Same
48.	SS036810	Slurry Seal	Slurry Seal	Same
49.	SS036600	Slurry Seal	Slurry Seal	Same
50.	SS036900	Slurry Seal	Slurry Seal	Same
51.	SS036520	Slurry Seal	Slurry Seal	Same
52.	SS030160	Slurry Seal	Slurry Seal	Same
53.	SS034650	Slurry Seal	Slurry Seal	Same
54.	SS038250	Slurry Seal	Slurry Seal	Same
55.	SS035510	Slurry Seal	Slurry Seal	Same
56.	SS044430	Slurry Seal	Slurry Seal	Same
57.	SS028510	Slurry Seal	Slurry Seal	Same
58.	SS041950	Slurry Seal	Slurry Seal	Same
59.	SS041960	Slurry Seal	Slurry Seal	Same
60.	SS041970	Slurry Seal	Slurry Seal	Same
61.	SS036620	Slurry Seal	Slurry Seal	Same
62.	QS01-27	Slurry Seal	Slurry Seal	Same
63.	QS02-28	Slurry Seal	Slurry Seal	Same
64.	QS17-11	Slurry Seal	Slurry Seal	Same
65.	QS18-11	Slurry Seal	Slurry Seal	Same
66.	QS20-31	Slurry Seal	Slurry Seal	Same
67.	QS21-25	Slurry Seal	Slurry Seal	Same
68.	QS21-30	Slurry Seal	Slurry Seal	Same
69.	QS3-16	Slurry Seal	Slurry Seal	Same
70.	QS34-23	Slurry Seal	Slurry Seal	Same
71.	QS34-35	Slurry Seal	Slurry Seal	Same
72.	QS40-30	Slurry Seal	Slurry Seal	Same
73.	QS4-28	Slurry Seal	Slurry Seal	Same
74.	QS48-38	Slurry Seal	Slurry Seal	Same
75.	QS70-17	Slurry Seal	Slurry Seal	Same
76.	QS01-26	Slurry Seal	Slurry Seal	Same
77.	QS6-27	Slurry Seal	Slurry Seal	Same
78.	SS049260	Thin Overlay	Thin Overlay	Same
79.	SS010080	Thin Overlay	Thin Overlay	Same
80.	SS023600	Thin Overlay	Thin Overlay	Same
81.	SS007920	Thin Overlay	Thin Overlay	Same
82.	SS006420	Thin Overlay	Thin Overlay	Same

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
83.	SS031140	Thin Overlay	Thin Overlay	Same
84.	SS017350	Thin Overlay	Thin Overlay	Same
85.	SS035610	Thin Overlay	Thin Overlay	Same
86.	QS13-7	Thin Overlay	Thin Overlay	Same
87.	QS28-37	Thin Overlay	Thin Overlay	Same
88.	QS51-21	Thin Overlay	Thin Overlay	Same
89.	QS09-32	Thin Overlay	Thin Overlay	Same
90.	QS37-39	Thin Overlay	Thin Overlay	Same
91.	QS39-23	Thin Overlay	Thin Overlay	Same
92.	QS41-23	Thin Overlay	Thin Overlay	Same
93.	QS41-30	Thin Overlay	Thin Overlay	Same
94.	QS41-31	Thin Overlay	Thin Overlay	Same
95.	QS42-30	Thin Overlay	Thin Overlay	Same
96.	QS42-19	Thin Overlay	Thin Overlay	Same
97.	QS28-38	Thin Overlay	Thin Overlay	Same
98.	QS68-19	Thin Overlay	Thin Overlay	Same
99.	QS10-27	Thin Overlay	Thin Overlay	Same
100.	QS10-19	Thin Overlay	Thin Overlay	Same
101.	QS11-11	Thin Overlay	Thin Overlay	Same
102.	QS12-11	Thin Overlay	Thin Overlay	Same
103.	QS12-12	Thin Overlay	Thin Overlay	Same
104.	QS7-28	Thin Overlay	Thin Overlay	Same
105.	QS9-14	Thin Overlay	Thin Overlay	Same
106.	QS11-17	Thin Overlay	Thin Overlay	Same
107.	QS8-24	FAST	Fog Seal	Downgraded Treatment
108.	QS9-18	FAST	Fog Seal	Downgraded Treatment
109.	QS10-28	FAST	Slurry Seal	Downgraded Treatment
110.	QS42-27	FAST	Slurry Seal	Downgraded Treatment
111.	QS5-37	FAST	Slurry Seal	Downgraded Treatment
112.	QS6-17	FAST	Slurry Seal	Downgraded Treatment
113.	QS6-36	FAST	Slurry Seal	Downgraded Treatment
114.	QS7-26	FAST	Slurry Seal	Downgraded Treatment
115.	QS6-35	FAST	Slurry Seal	Downgraded Treatment
116.	QS32-26	FAST	Slurry Seal	Downgraded Treatment
117.	QS14-9	FAST	Slurry Seal	Downgraded Treatment
118.	QS7-37	FAST	Slurry Seal	Downgraded Treatment
119.	QS7-17	FAST	Slurry Seal	Downgraded Treatment
120.	SS020970	Slurry Seal	Fog Seal	Downgraded Treatment
121.	SS021230	Slurry Seal	Fog Seal	Downgraded Treatment
122.	SS013230	Slurry Seal	Fog Seal	Downgraded Treatment
123.	SS012950	Slurry Seal	Fog Seal	Downgraded Treatment

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
124.	SS025430	Slurry Seal	Fog Seal	Downgraded Treatment
125.	SS021890	Slurry Seal	Fog Seal	Downgraded Treatment
126.	SS025440	Slurry Seal	Fog Seal	Downgraded Treatment
127.	SS011510	Slurry Seal	Fog Seal	Downgraded Treatment
128.	SS022390	Slurry Seal	Fog Seal	Downgraded Treatment
129.	SS010630	Slurry Seal	Fog Seal	Downgraded Treatment
130.	SS010160	Slurry Seal	Fog Seal	Downgraded Treatment
131.	SS022980	Slurry Seal	Fog Seal	Downgraded Treatment
132.	SS026390	Slurry Seal	Fog Seal	Downgraded Treatment
133.	SS023430	Slurry Seal	Fog Seal	Downgraded Treatment
134.	SS045280	Slurry Seal	Fog Seal	Downgraded Treatment
135.	SS008780	Slurry Seal	Fog Seal	Downgraded Treatment
136.	SS007980	Slurry Seal	Fog Seal	Downgraded Treatment
137.	SS006050	Slurry Seal	Fog Seal	Downgraded Treatment
138.	SS030140	Slurry Seal	Fog Seal	Downgraded Treatment
139.	SS040590	Slurry Seal	Fog Seal	Downgraded Treatment
140.	SS039170	Slurry Seal	Fog Seal	Downgraded Treatment
141.	SS039250	Slurry Seal	Fog Seal	Downgraded Treatment
142.	SS026030	Slurry Seal	Fog Seal	Downgraded Treatment
143.	SS025370	Slurry Seal	Fog Seal	Downgraded Treatment
144.	SS041230	Slurry Seal	Fog Seal	Downgraded Treatment
145.	SS025290	Slurry Seal	Fog Seal	Downgraded Treatment
146.	SS038840	Slurry Seal	Fog Seal	Downgraded Treatment
147.	SS035630	Slurry Seal	Fog Seal	Downgraded Treatment
148.	SS040730	Slurry Seal	Fog Seal	Downgraded Treatment
149.	SS040760	Slurry Seal	Fog Seal	Downgraded Treatment
150.	SS028450	Slurry Seal	Fog Seal	Downgraded Treatment
151.	SS041640	Slurry Seal	Fog Seal	Downgraded Treatment
152.	SS041650	Slurry Seal	Fog Seal	Downgraded Treatment
153.	SS025460	Slurry Seal	Fog Seal	Downgraded Treatment
154.	QS6-8	Slurry Seal	Fog Seal	Downgraded Treatment
155.	SS010230	Slurry Seal	Seal Coat	Downgraded Treatment
156.	QS33-25	Slurry Seal	Seal Coat	Downgraded Treatment
157.	SS014260	Thin Overlay	Fog Seal	Downgraded Treatment
158.	SS021200	Thin Overlay	Fog Seal	Downgraded Treatment
159.	SS023590	Thin Overlay	Fog Seal	Downgraded Treatment
160.	SS007950	Thin Overlay	Fog Seal	Downgraded Treatment
161.	SS037890	Thin Overlay	Fog Seal	Downgraded Treatment
162.	SS038870	Thin Overlay	Fog Seal	Downgraded Treatment
163.	SS041240	Thin Overlay	Fog Seal	Downgraded Treatment
164.	SS038830	Thin Overlay	Fog Seal	Downgraded Treatment

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
165.	QS40-23	Thin Overlay	Fog Seal	Downgraded Treatment
166.	QS04-24	Thin Overlay	Fog Seal	Downgraded Treatment
167.	QS5-13	Thin Overlay	Fog Seal	Downgraded Treatment
168.	SS021770	Thin Overlay	Slurry Seal	Downgraded Treatment
169.	SS021970	Thin Overlay	Slurry Seal	Downgraded Treatment
170.	SS006980	Thin Overlay	Slurry Seal	Downgraded Treatment
171.	SS024138	Thin Overlay	Slurry Seal	Downgraded Treatment
172.	SS039200	Thin Overlay	Slurry Seal	Downgraded Treatment
173.	SS030350	Thin Overlay	Slurry Seal	Downgraded Treatment
174.	SS034640	Thin Overlay	Slurry Seal	Downgraded Treatment
175.	SS025790	Thin Overlay	Slurry Seal	Downgraded Treatment
176.	SS025770	Thin Overlay	Slurry Seal	Downgraded Treatment
177.	SS038000	Thin Overlay	Slurry Seal	Downgraded Treatment
178.	SS038030	Thin Overlay	Slurry Seal	Downgraded Treatment
179.	SS037510	Thin Overlay	Slurry Seal	Downgraded Treatment
180.	SS038270	Thin Overlay	Slurry Seal	Downgraded Treatment
181.	SS038320	Thin Overlay	Slurry Seal	Downgraded Treatment
182.	SS044610	Thin Overlay	Slurry Seal	Downgraded Treatment
183.	SS033650	Thin Overlay	Slurry Seal	Downgraded Treatment
184.	SS027990	Thin Overlay	Slurry Seal	Downgraded Treatment
185.	SS027930	Thin Overlay	Slurry Seal	Downgraded Treatment
186.	QS15-7	Thin Overlay	Slurry Seal	Downgraded Treatment
187.	QS31-36	Thin Overlay	Slurry Seal	Downgraded Treatment
188.	QS03-24	Thin Overlay	Slurry Seal	Downgraded Treatment
189.	QS10-39	Thin Overlay	Slurry Seal	Downgraded Treatment
190.	QS14-23	Thin Overlay	Slurry Seal	Downgraded Treatment
191.	QS26-31	Thin Overlay	Slurry Seal	Downgraded Treatment
192.	QS33-26	Thin Overlay	Slurry Seal	Downgraded Treatment
193.	QS34-44	Thin Overlay	Slurry Seal	Downgraded Treatment
194.	QS17-4	Thin Overlay	Slurry Seal	Downgraded Treatment
195.	QS49-13	Thin Overlay	Slurry Seal	Downgraded Treatment
196.	QS10-20	Fog Seal	FAST	Upgraded Treatment
197.	QS10-41	Fog Seal	Slurry Seal	Upgraded Treatment
198.	QS19-42	Fog Seal	Slurry Seal	Upgraded Treatment
199.	QS5-11	Fog Seal	Slurry Seal	Upgraded Treatment
200.	QS5-12	Fog Seal	Slurry Seal	Upgraded Treatment
201.	QS17-2	Fog Seal	Slurry Seal	Upgraded Treatment
202.	QS34-26	Fog Seal	Thin Overlay	Upgraded Treatment
203.	QS011-27	Fog Seal	Thin Overlay	Upgraded Treatment
204.	QS5-30	Seal Coat	Slurry Seal	Upgraded Treatment
205.	SS014340	Slurry Seal	FAST	Upgraded Treatment

No.	Super Section or Quarter Section ID	PMS Recommended Treatment	Field Recommended Treatment	Comment
206.	SS014310	Slurry Seal	FAST	Upgraded Treatment
207.	SS014540	Slurry Seal	FAST	Upgraded Treatment
208.	SS010090	Slurry Seal	FAST	Upgraded Treatment
209.	SS008900	Slurry Seal	FAST	Upgraded Treatment
210.	SS034620	Slurry Seal	FAST	Upgraded Treatment
211.	SS035590	Slurry Seal	FAST	Upgraded Treatment
212.	SS023470	Slurry Seal	Thin Overlay	Upgraded Treatment
213.	SS006080	Slurry Seal	Thin Overlay	Upgraded Treatment
214.	SS006060	Slurry Seal	Thin Overlay	Upgraded Treatment
215.	QS8-9	Slurry Seal	Thin Overlay	Upgraded Treatment
216.	QS15-9	Slurry Seal	Thin Overlay	Upgraded Treatment
217.	QS13-6	Slurry Seal	Thin Overlay	Upgraded Treatment
218.	QS16-7	Slurry Seal	Thin Overlay	Upgraded Treatment
219.	QS09-31	Slurry Seal	Thin Overlay	Upgraded Treatment
220.	QS7-9	Slurry Seal	Thin Overlay	Upgraded Treatment
221.	QS012-27	Slurry Seal	Thin Overlay	Upgraded Treatment

APPENDIX C

CITY OF PHOENIX HISTORICAL DAILY LOW AND HIGH TEMPERATURES

Date	Low Temp (°C)	High Temp (°C)
1/1/2017	11.1	13.9
1/2/2017	8.9	14.4
1/3/2017	7.2	16.1
1/4/2017	7.8	19.4
1/5/2017	8.3	20.0
1/6/2017	9.4	18.9
1/7/2017	6.1	18.9
1/8/2017	10.0	23.3
1/9/2017	11.1	19.4
1/10/2017	9.4	21.1
1/11/2017	10.0	18.9
1/12/2017	7.8	20.6
1/13/2017	12.8	18.9
1/14/2017	12.2	18.3
1/15/2017	10.0	15.6
1/16/2017	10.0	17.8
1/17/2017	7.2	17.2
1/18/2017	7.2	19.4
1/19/2017	8.3	13.9
1/20/2017	8.9	11.7
1/21/2017	7.8	15.6
1/22/2017	6.7	16.1
1/23/2017	9.4	17.2
1/24/2017	5.6	14.4
1/25/2017	3.3	13.9
1/26/2017	2.8	14.4
1/27/2017	2.8	15.0
1/28/2017	1.7	17.8
1/29/2017	4.4	22.2
1/30/2017	6.7	24.4
1/31/2017	8.3	23.3
2/1/2017	7.8	23.9
2/2/2017	9.4	22.8
2/3/2017	10.0	22.2
2/4/2017	8.3	23.9
2/5/2017	7.8	24.4
2/6/2017	11.7	19.4
2/7/2017	10.6	22.8
2/8/2017	11.1	25.0
2/9/2017	12.2	27.8
2/10/2017	12.2	28.3
2/11/2017	15.0	26.1
2/12/2017	15.6	23.3
2/13/2017	15.0	23.3
2/14/2017	13.9	23.3
2/15/2017	15.0	23.9

Date	Low Temp (°C)	High Temp (°C)
2/16/2017	11.1	23.9
2/17/2017	13.9	23.9
2/18/2017	10.0	19.4
2/19/2017	10.0	15.6
2/20/2017	10.0	20.6
2/21/2017	11.1	24.4
2/22/2017	12.2	25.0
2/23/2017	8.3	17.2
2/24/2017	6.1	17.8
2/25/2017	5.6	19.4
2/26/2017	11.1	21.1
2/27/2017	8.9	18.3
2/28/2017	11.1	18.3
3/1/2017	7.2	21.1
3/2/2017	8.3	25.0
3/3/2017	11.7	25.0
3/4/2017	11.7	26.1
3/5/2017	14.4	23.9
3/6/2017	11.1	20.0
3/7/2017	8.3	23.9
3/8/2017	10.6	28.3
3/9/2017	12.8	30.0
3/10/2017	13.9	31.1
3/11/2017	15.6	31.7
3/12/2017	14.4	31.1
3/13/2017	16.1	33.3
3/14/2017	17.2	33.9
3/15/2017	17.8	32.8
3/16/2017	16.7	33.9
3/17/2017	17.8	33.9
3/18/2017	17.8	35.0
3/19/2017	17.8	35.6
3/20/2017	19.4	35.6
3/21/2017	18.9	33.9
3/22/2017	17.2	27.8
3/23/2017	12.2	22.2
3/24/2017	11.1	25.6
3/25/2017	13.9	28.3
3/26/2017	13.3	27.8
3/27/2017	15.0	28.3
3/28/2017	13.9	26.1
3/29/2017	13.9	29.4
3/30/2017	14.4	32.2
3/31/2017	13.3	21.1
4/1/2017	11.1	22.8
4/2/2017	11.7	27.8

Date	Low Temp (°C)	High Temp (°C)
4/3/2017	15.0	29.4
4/4/2017	13.9	26.1
4/5/2017	13.9	29.4
4/6/2017	15.6	32.8
4/7/2017	17.2	32.2
4/8/2017	16.1	31.7
4/9/2017	16.1	26.7
4/10/2017	13.3	29.4
4/11/2017	14.4	31.7
4/12/2017	16.1	33.3
4/13/2017	18.3	34.4
4/14/2017	16.7	32.2
4/15/2017	16.1	31.1
4/16/2017	16.7	32.8
4/17/2017	16.7	33.9
4/18/2017	18.3	35.0
4/19/2017	21.1	32.2
4/20/2017	17.8	33.9
4/21/2017	16.7	35.0
4/22/2017	18.3	35.6
4/23/2017	20.0	37.2
4/24/2017	20.6	33.9
4/25/2017	20.6	30.6
4/26/2017	17.8	32.2
4/27/2017	20.0	32.2
4/28/2017	19.4	30.6
4/29/2017	14.4	27.2
4/30/2017	14.4	30.6
5/1/2017	16.7	34.4
5/2/2017	19.4	36.1
5/3/2017	20.6	37.8
5/4/2017	22.8	39.4
5/5/2017	24.4	42.2
5/6/2017	22.8	36.7
5/7/2017	17.8	23.3
5/8/2017	15.6	28.3
5/9/2017	13.9	24.4
5/10/2017	15.6	26.7
5/11/2017	17.8	32.2
5/12/2017	21.7	36.1
5/13/2017	21.7	37.2
5/14/2017	21.1	33.9
5/15/2017	20.6	31.1
5/16/2017	16.1	25.6
5/17/2017	16.7	30.6
5/18/2017	19.4	30.0

Date	Low Temp (°C)	High Temp (°C)
5/19/2017	16.7	30.6
5/20/2017	20.0	34.4
5/21/2017	21.1	38.3
5/22/2017	22.8	40.0
5/23/2017	25.0	40.0
5/24/2017	23.9	42.2
5/25/2017	26.1	38.9
5/26/2017	23.3	35.6
5/27/2017	21.1	35.6
5/28/2017	22.2	38.9
5/29/2017	22.8	40.0
5/30/2017	25.0	38.3
5/31/2017	24.4	38.3
6/1/2017	25.6	37.2
6/2/2017	23.9	38.9
6/3/2017	25.6	41.7
6/4/2017	27.8	41.7
6/5/2017	28.3	41.7
6/6/2017	28.9	41.7
6/7/2017	27.8	41.1
6/8/2017	25.6	40.6
6/9/2017	26.1	41.1
6/10/2017	25.6	38.9
6/11/2017	24.4	38.3
6/12/2017	24.4	33.9
6/13/2017	20.6	35.6
6/14/2017	21.1	39.4
6/15/2017	22.8	42.2
6/16/2017	24.4	42.8
6/17/2017	25.6	43.3
6/18/2017	26.7	44.4
6/19/2017	28.9	47.8
6/20/2017	30.0	48.3
6/21/2017	32.2	47.2
6/22/2017	32.8	45.0
6/23/2017	30.6	44.4
6/24/2017	31.1	46.7
6/25/2017	33.9	46.7
6/26/2017	32.8	44.4
6/27/2017	30.0	43.3
6/28/2017	28.9	42.2
6/29/2017	28.3	42.2
6/30/2017	28.3	42.8
7/1/2017	26.7	44.4
7/2/2017	28.3	43.3
7/3/2017	31.1	41.7

Date	Low Temp (°C)	High Temp (°C)
7/4/2017	31.1	43.9
7/5/2017	30.6	44.4
7/6/2017	31.1	43.9
7/7/2017	32.8	47.8
7/8/2017	35.0	45.0
7/9/2017	30.6	42.8
7/10/2017	31.1	42.8
7/11/2017	27.8	40.0
7/12/2017	29.4	42.2
7/13/2017	30.6	42.8
7/14/2017	30.0	42.2
7/15/2017	30.6	42.8
7/16/2017	23.3	40.0
7/17/2017	24.4	37.2
7/18/2017	26.1	39.4
7/19/2017	27.8	38.9
7/20/2017	28.3	39.4
7/21/2017	28.3	39.4
7/22/2017	28.3	41.1
7/23/2017	24.4	39.4
7/24/2017	23.9	32.2
7/25/2017	26.7	38.9
7/26/2017	28.9	41.1
7/27/2017	31.7	43.3
7/28/2017	29.4	38.3
7/29/2017	28.3	39.4
7/30/2017	26.7	37.2
7/31/2017	29.4	41.7
8/1/2017	30.6	38.3
8/2/2017	27.2	35.6
8/3/2017	23.3	40.0
8/4/2017	24.4	39.4
8/5/2017	28.3	41.1
8/6/2017	28.9	40.6
8/7/2017	28.3	41.7
8/8/2017	27.8	42.2
8/9/2017	29.4	43.9
8/10/2017	31.7	40.6
8/11/2017	27.8	42.2
8/12/2017	26.7	39.4
8/13/2017	22.8	37.2
8/14/2017	26.1	39.4
8/15/2017	28.3	38.9
8/16/2017	25.6	39.4
8/17/2017	25.6	40.0
8/18/2017	26.1	41.1

Date	Low Temp (°C)	High Temp (°C)
8/19/2017	27.2	40.6
8/20/2017	28.9	38.9
8/21/2017	29.4	40.0
8/22/2017	28.3	42.2
8/23/2017	25.6	41.7
8/24/2017	26.1	40.0
8/25/2017	29.4	42.2
8/26/2017	30.6	43.3
8/27/2017	31.7	43.9
8/28/2017	32.2	43.3
8/29/2017	31.1	42.8
8/30/2017	31.7	42.2
8/31/2017	30.0	42.2
9/1/2017	29.4	43.3
9/2/2017	28.9	38.9
9/3/2017	28.3	39.4
9/4/2017	27.8	40.0
9/5/2017	29.4	42.2
9/6/2017	30.0	42.8
9/7/2017	29.4	40.6
9/8/2017	27.2	36.7
9/9/2017	26.7	36.1
9/10/2017	26.7	40.6
9/11/2017	31.1	42.2
9/12/2017	30.0	43.3
9/13/2017	30.0	42.2
9/14/2017	29.4	38.3
9/15/2017	25.0	36.7
9/16/2017	23.3	36.1
9/17/2017	25.0	36.7
9/18/2017	22.2	37.2
9/19/2017	21.7	37.8
9/20/2017	22.2	37.2
9/21/2017	22.2	36.7
9/22/2017	22.8	32.2
9/23/2017	18.9	30.0
9/24/2017	16.7	30.0
9/25/2017	16.7	31.7
9/26/2017	17.2	31.7
9/27/2017	20.0	33.3
9/28/2017	19.4	34.4
9/29/2017	20.6	36.7
9/30/2017	21.7	36.7
10/1/2017	20.6	36.7
10/2/2017	20.6	33.3
10/3/2017	20.6	36.1

Date	Low Temp (°C)	High Temp (°C)
10/4/2017	21.1	37.2
10/5/2017	23.9	36.7
10/6/2017	20.6	36.1
10/7/2017	18.9	35.6
10/8/2017	18.3	34.4
10/9/2017	18.9	31.7
10/10/2017	16.7	32.8
10/11/2017	21.7	36.7
10/12/2017	18.9	34.4
10/13/2017	20.0	35.0
10/14/2017	19.4	34.4
10/15/2017	18.3	36.1
10/16/2017	20.6	37.2
10/17/2017	22.2	36.1
10/18/2017	21.7	35.6
10/19/2017	23.3	35.6
10/20/2017	20.0	31.7
10/21/2017	18.9	29.4
10/22/2017	16.1	33.3
10/23/2017	17.2	36.1
10/24/2017	19.4	37.2
10/25/2017	21.7	34.4
10/26/2017	18.9	33.9
10/27/2017	16.1	33.3
10/28/2017	17.8	33.3
10/29/2017	18.3	32.8
10/30/2017	17.2	30.0
10/31/2017	17.2	27.8
11/1/2017	17.2	28.9
11/2/2017	17.8	27.8
11/3/2017	15.6	27.2
11/4/2017	20.0	27.8
11/5/2017	17.2	26.1
11/6/2017	15.0	28.3
11/7/2017	18.3	27.2
11/8/2017	17.8	28.3
11/9/2017	17.8	29.4
11/10/2017	16.1	30.0
11/11/2017	15.0	29.4
11/12/2017	14.4	30.0
11/13/2017	17.8	31.1
11/14/2017	15.6	30.6
11/15/2017	14.4	28.9
11/16/2017	15.6	30.0
11/17/2017	16.7	26.7
11/18/2017	13.3	26.1

Date	Low Temp (°C)	High Temp (°C)
11/19/2017	11.1	27.8
11/20/2017	12.2	26.1
11/21/2017	12.8	26.1
11/22/2017	12.8	31.1
11/23/2017	15.0	30.6
11/24/2017	14.4	30.0
11/25/2017	14.4	30.0
11/26/2017	13.9	31.7
11/27/2017	13.9	27.8
11/28/2017	11.7	23.3
11/29/2017	13.9	25.0
11/30/2017	16.7	24.4
12/1/2017	16.1	25.6
12/2/2017	14.4	28.9
12/3/2017	13.9	26.7
12/4/2017	11.7	22.8
12/5/2017	10.0	18.9
12/6/2017	10.0	23.9
12/7/2017	9.4	18.9
12/8/2017	5.6	18.9
12/9/2017	6.1	24.4
12/10/2017	15.6	25.6
12/11/2017	11.1	24.4
12/12/2017	7.8	23.9
12/13/2017	7.8	25.0
12/14/2017	7.2	23.3
12/15/2017	10.0	22.2
12/16/2017	9.4	19.4
12/17/2017	10.0	16.1
12/18/2017	7.8	19.4
12/19/2017	6.7	19.4
12/20/2017	7.2	20.0
12/21/2017	6.1	13.9
12/22/2017	2.2	14.4
12/23/2017	3.9	16.1
12/24/2017	5.0	21.1
12/25/2017	6.1	18.9
12/26/2017	5.0	21.1
12/27/2017	7.8	22.8
12/28/2017	6.1	23.9
12/29/2017	7.2	25.0
12/30/2017	8.3	25.0
12/31/2017	7.2	21.1
1/1/2018	6.1	22.8
1/2/2018	8.9	23.9
1/3/2018	8.3	24.4

Date	Low Temp (°C)	High Temp (°C)
1/4/2018	13.3	26.1
1/5/2018	10.0	25.0
1/6/2018	10.6	23.3
1/7/2018	11.7	23.9
1/8/2018	12.2	23.9
1/9/2018	12.2	26.7
1/10/2018	11.1	18.3
1/11/2018	8.9	21.1
1/12/2018	8.9	22.2
1/13/2018	8.3	25.6
1/14/2018	8.9	26.1
1/15/2018	9.4	23.9
1/16/2018	10.6	23.3
1/17/2018	11.1	22.2
1/18/2018	7.8	23.9
1/19/2018	8.9	25.0
1/20/2018	10.0	16.1
1/21/2018	5.0	14.4
1/22/2018	4.4	16.1
1/23/2018	4.4	21.1
1/24/2018	9.4	24.4
1/25/2018	7.8	25.0
1/26/2018	8.3	20.0
1/27/2018	6.1	22.8
1/28/2018	7.2	26.7
1/29/2018	12.8	28.3
1/30/2018	10.6	27.8
1/31/2018	10.0	27.2
Min	1.7	11.7
Max	35.0	48.3

APPENDIX D

WIDE CRACKING LOCATIONS

Location No.	Street Or Quarter Section	From	To	Soil Properties	Soil Type
1.	QS 1-16 & QS 2-16	Baseline Rd / Southern Ave	55th Ave / 51st Ave	Flooding, Low strength, Shrink-swell	Gilman fine sandy loam, Gilman loam, Glenbar clay loam
2.	QS 5-4	Broadway Rd / Raymond St	103rd Ave / 99th Ave	Flooding, Low strength, Shrink-swell	Estrella loam, Gilman fine sandy loam, Toltec loam, Tucson loam, Tucson clay loam
3.	QS 10-13	Union Pacific Rr / Van Buren	67th Ave / 63rd Ave	Flooding, Low strength, Shrink-swell	Glenbar clay loam
4.	QS 13-22	McDowell Rd / Encanto Blvd	31st Ave / 27th Ave	Flooding, Low strength, Shrink-swell	Avondale clay loam, Glenbar clay loam
5.	QS 40-25	Utopia Rd / Beardsley Rd	19th Ave / 15th Ave	Flooding, Low strength, Shrink-swell	Estrella loam, Mohall loam MLRA 40, Tremant gravelly loam
6.	7th Ave	Union Hills Dr	Pima Frwy (SR 101)	Flooding, Low strength, Shrink-swell	Estrella loam, Mohall loam MLRA 40
7.	12th ST	Bethany Home Rd	Glendale Ave	Flooding, Low strength, Shrink-swell	Antho gravelly sandy loam, Estrella loam, Gilman loam
8.	12th St	Campell Ave	Bethany Home Rd	Flooding, Low strength, Shrink-swell	Estrella loam, Gilman loam, Mohall loam MLRA 40
9.	15th Ave	Glendale Ave	Northern Ave	Flooding, Low strength, Shrink-swell	Estrella loam, Gilman loam, Laveen loam
10.	19th Ave	Pinnacle Peak Rd	Jomax Rd	Flooding, Low strength, Shrink-swell	Estrella loams, Tremant gravelly sandy loams, Tremant-Rillito complex, Tremant complex
11.	27th Ave	Glendale Ave	Butler Dr	Flooding, Low strength, Shrink-swell	Estrella loam, Mohall loam MLRA 40, Mohall clay loam, Trix clay loam

Location No.	Street Or Quarter Section	From	To	Soil Properties	Soil Type
12.	107th Ave	Camelback Rd	Bethany Home Rd	Flooding, Low strength, Shrink-swell	Gilman loam, Glenbar clay loam, Gunsight-Rillito complex
13.	Grand Ave	Roosevelt St / 15th Ave	Willetta St / 18th Ave	Flooding, Low strength, Shrink-swell	Glenbar clay loam, Cashion clay
14.	Happy Valley Rd	35th Ave	19th Ave	Flooding, Low strength, Shrink-swell	Estrella loam, Tremant complex, Tremant-Rillito complex
15.	Union Hills Dr	19th Ave	7th Ave	Flooding, Low strength, Shrink-swell	Estrella loam, Mohall loam MLRA 40
16.	63rd Ave	Broadway Rd	Lower Buckeye Rd	Flooding, Low strength, Shrink-swell	Avondale clay loam, Gilman loam, Glenbar clay loam
17.	17th Ave	Ed Pastor Frwy (SR 202)	Chandler Blvd	Flooding, Shrink-swell, Large stones	Carrizo-Ebon complex, Ebon gravelly loam
18.	QS 12-27	Roosevelt St / Mcdowell Rd	7th Ave / Central Ave	Low strength, Shrink-swell	Gilman loam, Mohall clay loam
19.	QS 19-25	Camelback Rd / Missouri Ave	19th Ave / 15th Ave	Low strength, Shrink-swell	Laveen loam, Mohall loam MLRA 40
20.	QS 45-16	Pinnacle Peak Rd / Alameda Rd	55th Ave / 51st Ave	Low strength, Shrink-swell	Laveen loam, Mohall loam MLRA 40
21.	QS 50-21	Pinnacle Vista Dr / Dynamite Blvd	35th Ave / 31st Ave	Low strength, Shrink-swell	Carefree cobbly clay loam, Suncity-Cipriano complex
22.	QS 70-17	Magellan Dr / Circle Mountain Rd	51st Ave / 47th Dr	Low strength, Shrink-swell	Suncity-Cipriano complex, Ebon very gravelly loam
23.	15th Ave	Thomas Rd	Indian School Rd	Low strength, Shrink-swell	Mohall clay loam
24.	32nd St	Bell Rd	Union Hills Dr	Low strength, Shrink-swell	Estrella loams, Glenbar loams, Mohall loam, calcareous solum; Momoli gravelly sandy loam, Rillito loam
25.	35th Ave	Alameda Rd	Hackamore Dr	Low strength, Shrink-swell	Mohall loam MLRA 40, Tremant gravelly clay loam, Tremant-Rillito complex

Location No.	Street Or Quarter Section	From	To	Soil Properties	Soil Type
26.	43rd Ave	Buckeye Rd	Van Buren St	Low strength, Shrink-swell	Mohall clay loam, Mohall clay, Trix clay loam
27.	43rd Ave	Thunderbird Rd	Union Hills Rd	Low strength, Shrink-swell	Laveen loam, Mohall clay loam
28.	43rd Ave	Anthem Wy	End Of Road	Low strength, Shrink-swell	Carefree cobbly clay loam, Carefree-Beardsley complex
29.	83rd Ave	Lower Buckeye Rd	Buckeye Rd	Low strength, Shrink-swell	Mohall loam MLRA 40, Mohall clay loam
30.	Bell Rd	Tatum Blvd	56th St	Low strength, Shrink-swell	Gilman loam, Glenbar loams
31.	Bethany Home Rd	Black Canyon Frwy (I-17)	Central Ave	Low strength, Shrink-swell	Gilman loam, Laveen loam, Mohall loam MLRA 40
32.	Black Mountain Blvd	Desert Forest Trl	Carefree Hwy	Low strength, Shrink-swell	Carefree cobbly clay loam, Ebon very gravelly loam, Pinaleno-Tres Hermanos complex
33.	Camelback Rd	107th Ave	99th Ave	Low strength, Shrink-swell	Laveen loam,Laveen clay loam, Mohall loam MLRA 40, Trix clay loam
34.	Carefree Hwy	Black Canyon Frwy (I-17)	7th Ave	Low strength, Shrink-swell	Carefree cobbly clay loam, Carefree-Beardsley complex, Ebon very gravelly loam, Gunsight-Cipriano complex, Vaiva very gravelly loam
35.	Dunlap Ave	Black Canyon Frwy (I-17)	23rd Ave	Low strength, Shrink-swell	Gilman loam, Laveen loam, Mohall loam MLRA 40, Trix clay loam
36.	Greenway Rd	51st Ave	43rd Ave	Low strength, Shrink-swell	Laveen loam, Mohall clay loam
37.	North Valley Pkwy	Dove Valley Rd	End Of Road	Low strength, Shrink-swell	Carefree cobbly clay loam, Ebon very gravelly loam
38.	Paloma Pkwy	Sonoran Blvd	Dove Valley Rd	Low strength, Shrink-swell	Carefree cobbly clay loam, Ebon very gravelly loam, Gunsight-Cipriano complex
39.	Runion Dr	29th Ave	27th Ave	Low strength, Shrink-swell	Mohall clay loam
40.	Thunderbird Rd	32nd St	40th St	Low strength, Shrink-swell	Estrella loams, Gilman loams, Glenbar loams, Mohall loam, calcareous solum
41.	Thunderbird Rd	51st Ave	43rd Ave	Low strength, Shrink-swell	Laveen loam, 0 to 1 percent slopes, Mohall loam MLRA 40, Mohall clay loam, Vecont clay

Location No.	Street Or Quarter Section	From	To	Soil Properties	Soil Type
42.	QS 59-23 & QS 60-23	Carefree Hwy / Languid Ln	Open Space / 27th Ln	Shrink-swell, Depth to hard and soft bedrock, Slope	Vaiva very gravelly loam, Ebon very gravelly loam,
43.	QS 57-23 & QS 58-23	Dove Valley Rd / Carefree Hwy	27th Dr / 21st Dr	Shrink-swell	Ebon very gravelly loam, Pinamt-Tremant complex
44.	Bell Rd	Cave Creek Rd	32nd St	Shrink-swell	Estrella loams, Mohall loam, calcareous solum, Rillito loam
45.	Dove Valley Rd	North Valley Pkwy	22nd Ave	Shrink-swell	Ebon very gravelly loam, Pinamt-Tremant complex
46.	Lone Mountain Rd	40th St	Cave Creek Rd	Shrink-swell	Ebon very gravelly loam, Pinamt-Tremant complex
47.	Pinnacle Peak Rd	Cave Creek Rd	40th St	Shrink-swell	Gilman loam, Momoli gravelly sandy loam, Tremant gravelly sandy loams, Tremant-Rillito complex
48.	Pinnacle Peak Rd	19th Ave	11st Ave	Shrink-swell	Tremant gravelly sandy loams
49.	Rancho Paloma Dr	Black Mountain Blvd	Cave Creek Rd	Shrink-swell	Eba very gravelly loam, Pinamt-Tremant complex
50.	QS 012-22	Pecos Rd / Shaughnessey Rd	31st Ave / Chandler Blvd	Flooding, Low strength, Shrink-swell*	Antho-Carrizo complex, Estrella loam*
51.	QS 18-1 & QS 18-2	Campbell Ave / Camelback Rd	113rd Dr / 107th Ave	Low strength, Shrink-swell*	Agualt loam, Avondale clay loam, Gilman loam, Mohall loam MLRA 40*
52.	Southern Ave	7th Ave	7th St	Low strength, Shrink-swell*	Agualt loam, Avondale clay loam, Gilman loam, Mohall loam MLRA 40*
53.	Shea Blvd	40th St	56th St	Shrink-swell*	Gilman loam, Mohall loam, calcareous solum*
54.	40th St	End Of Road	Pinnacle Peak Rd	Dusty, Low strength, Shrink-swell**	Gilman loam, Momoli gravelly sandy loam, Mohall loam**
55.	67th Ave	Happy Valley Rd	Jomax Rd	Low strength, Shrink-swell**	Antho-Carrizo complex, Gunsight-Pinal complex, Tremant gravelly sandy loams**

Location No.	Street Or Quarter Section	From	To	Soil Properties	Soil Type
56.	Dunlap Ave	23rd Ave	C Street	Low strength**, Shrink-swell**	Laveen loam, 0 to 1 percent slopes, Valencia sandy loam; Mohall loam MLRA 40**
57.	QS 4-33	Roeser Rd / Broadway Rd	24th St / 28th St	Dusty, Low strength, Sandiness	Avondale clay loam, Pinamt very gravelly loam
58.	QS 48-17	Parsons Rd / Deem Hills Pkwy	Stetson Valley Pkwy / 49th Ln	Dusty, Low strength	Coolidge-Laveen association, Pinal gravelly loam
59.	18th St	Camelback Rd	Colter St	Dusty, Low strength	Gilman loam
60.	35th Ave	Indian School Rd	Camelback Rd	Dusty, Low strength	Gilman loam
61.	Deer Valley Rd	Tatum Blvd	56th St	Dusty, Low strength	Gilman loam
62.	Galvin Pkwy	Van Buren St	Mcdowell Rd	Low strength	Cavelt gravelly loam, Rough broken land
63.	Mayo Blvd	Tatum Blvd	Scottsdale Rd	Dusty, Low strength	Gilman loam
64.	Pinnacle Vista Dr	Inspiration Mountain Pkwy	Pyramid Peak Pkwy	Low strength	Gunsight-Cipriano complex, Pinamt-Tremant complex, Suncity-Cipriano complex
65.	QS 09-32	Taxidea Way / Granite View Dr	20th Pl / 24th St	Not rated	Rough broken land
66.	24th St	Pecos Rd	Chandler Blvd	Not rated	Rock land
67.	QS 02-33	Valley View Dr / Highline Canal	24th St / 28th St	Not limited / Not rated	Antho gravelly sandy loam, Gravelly alluvial land, Tremant gravelly loam
68.	QS 09-37	Thistle Landing Dr / Ray Rd	41st Pl / 43rd Pl	Not limited	Antho sandy loam, Antho gravelly sandy loam
69.	56th St	Pima Frwy (SR 101)	Deer Valley Rd	Not limited	Gilman loam
70.	South Mountain Ave	15th Ave	7th Ave	Not limited	Rillito loam, Coolidge sandy loam, Tremant gravelly loam

Note: * Composed of less than 10% of the soil type.
** Soil type not found in the project location but in a close proximilty.
"Not limited" indicates the soil type that are suitable for the road constructions and to support the traffic.

APPENDIX E

FIELD REVIEW OF REFLECTIVE CRACKING

No.	Street or Quarter Section	From	To	Major Treatment	Major Treatment Completion Date	Secondary Treatment (* Pre-Treatment)	Secondary Treatment Completion Date	Field Review Date	Yr Since Last Major Treatment	Visible Reflective Cracking
1.	QS 35-31	Greenway Rd / Greenway Pkwy	16th St / 20th St	FAST	05/22/20	None		10/27/21	1.43	Yes
2.	Osborn Rd	35th Ave	27th Ave	FAST	03/29/19	None		10/27/21	2.58	No
3.	QS 45-17	Pinnacle Peak Rd / Misty Willow Ln	51st Ave / 47th Ave	FAST	03/25/21	Seal Coat	05/03/21	10/20/21	0.57	Yes
4.	QS 12-25	Roosevelt St / Mcdowell Rd	19th Ave / 15th Ave	FAST	03/24/21	Seal Coat	04/22/21	10/27/21	0.59	Yes
5.	QS 2-30	Vineyard Rd / Southern Ave	12th St / 16th St	FAST	03/19/21	Seal Coat	04/07/21	10/27/21	0.61	Yes
6.	QS 8-26	Maricopa Frwy (I-17) / Buckeye Rd	15th Ave / 7th Ave	FAST	05/27/20	Seal Coat	09/15/20	10/27/21	1.42	Yes
7.	QS 46-17	Alameda Rd / Happy Valley Rd	51st Ave / 47th Ave	FAST	05/01/20	Seal Coat	09/09/20	10/18/21	1.46	Yes
8.	QS 10-25	Jackson St / Van Buren St	19th Ave / 15th Ave	FAST	03/23/20	Seal Coat	09/08/20	10/27/21	1.60	Yes
9.	QS 02-33	Valley View Dr/ Highline Canal	24th St / 28th St	FAST	04/23/19	Seal Coat	09/11/19	10/20/21	2.49	Yes
10.	QS 41-29	Beardsley Rd / Rose Garden Ln	7th St / 12th St	FAST	03/26/21	Slurry Seal	06/22/21	10/27/21	0.59	Yes
11.	QS 45-16	Pinnacle Peak Rd / Alameda Rd	55th Ave / 51st Ave	FAST	03/16/21	Slurry Seal	03/16/21	10/18/21	0.59	Yes
12.	QS 17-24	Indian School Rd / Campbell Ave	23rd Ave / 19th Ave	FAST	03/17/21	Slurry Seal	03/17/21	10/27/21	0.61	Yes
13.	QS 8-29	Durango St / Buckeye Rd	7th St / 12th St	FAST	03/16/21	Slurry Seal	03/16/21	10/27/21	0.62	Yes
14.	QS 4-33	Roeser Rd / Broadway Rd	24th St / 28th St	FAST	03/02/21	Slurry Seal	03/25/21	10/20/21	0.64	Yes
15.	QS 15-23	Thomas Rd / Osborn Rd	27th Ave / Black Canyon Frwy (I-17)	FAST	03/04/21	Slurry Seal	03/19/21	10/27/21	0.65	Yes
16.	South Mountain Ave	15th Ave	7th Ave	FAST	05/22/20	Slurry Seal	05/22/20	10/20/21	1.41	Yes
17.	63rd Ave	Broadway Rd	Lower Buckeye Rd	FAST	05/22/20	Slurry Seal	05/22/20	10/27/21	1.43	Yes
18.	QS 50-21	Pinnacle Vista Dr / Dynamite Blvd	35th Ave / 31st Ave	FAST	05/12/20	Slurry Seal	05/20/20	10/18/21	1.43	Yes
19.	107th Ave	Camelback Rd	Bethany Home Rd	FAST	03/29/19	Slurry Seal	05/22/20	10/27/21	2.58	Yes
20.	Pinnacle Peak Rd	19th Ave	11th Ave	FAST	10/30/20	Micro Seal	11/05/20	10/18/21	0.97	Yes

No.	Street or Quarter Section	From	To	Major Treatment	Major Treatment Completion Date	Secondary Treatment (* Pre-Treatment)	Secondary Treatment Completion Date	Field Review Date	Yr Since Last Major Treatment	Visible Reflective Cracking
1.	QS 23-27	Glendale Ave / Orangewood Ave	7th Ave / Central Ave	Thin Overlay	08/07/17	None		08/23/17	0.04	No
2.	QS 03-26	Olney Ave / Dobbins Rd	15th Ave / 7th Ave	Thin Overlay	12/08/17	None		01/23/18	0.13	No
3.	QS 1-27	Baseline Rd / Vineyard Rd	7th Ave / Central Ave	Thin Overlay	12/08/17	None		02/05/18	0.16	No
4.	QS 03-38 & QS 03-39	Mineral Rd / Estes Way	44th St / 48th St	Thin Overlay	09/29/17	None		02/12/18	0.37	Yes
5.	QS 3-25	Southern Ave / Roeser Rd	19th Ave / 15th Ave	Thin Overlay	05/16/17	None		12/06/17	0.56	Yes
6.	QS 12-20	Roosevelt St / Mcdowell Rd	39th Ave / 35th Ave	Thin Overlay	01/20/17	None		10/30/17	0.78	Yes
7.	QS 4-30	Roeser Rd / Broadway Rd	12th St / 16th St	Thin Overlay	09/19/16	None		11/08/17	1.14	Yes
8.	QS 16-34	Osborn Rd / Indian School Rd	28th St / 32nd St	Thin Overlay	11/24/15	None		04/04/17	1.36	Yes
9.	QS 12-29	Roosevelt St / Mcdowell Rd	7th St / 12th St	Thin Overlay	11/24/15	None		10/19/17	1.90	Yes
10.	QS 21-23	Bethany Home Rd / Maryland Ave	27th Ave / 23rd Ave	Thin Overlay	02/04/19	Fog Seal	03/17/21	03/14/22	3.10	Yes
11.	QS 29-30 & QS 30-30	Peoria Ave / Sunnyside Dr	12th St / 16th St	Thin Overlay	08/10/18	Fog Seal	06/15/21	03/14/22	3.59	Yes
12.	QS 33-41	Thunderbird Rd / Acoma Dr	56th St / 60th St	Thin Overlay	06/07/18	Fog Seal	09/13/21	03/14/22	3.77	Yes
13.	QS 41-34 & QS 41-35	Beardsley Rd / Tonopah Dr	28th St / 34th St	Thin Overlay	03/13/18	Fog Seal	12/22/21	03/14/22	4.00	Yes
14.	QS 38-21	Grovers Ave / Union Hills Dr	35th Ave / 31st Ave	Thin Overlay	12/06/17	Fog Seal	12/08/21	03/14/22	4.27	Yes
15.	QS 27-19	Dunlap Ave / Purdue Ave	43rd Ave / 39th Ave	Thin Overlay	11/22/17	Fog Seal	04/30/21	03/14/22	4.31	Yes
16.	QS 11-22	Van Buren St / Roosevelt St	31st Ave / 27th Ave	Thin Overlay	10/24/19	Cool Seal	08/24/20	03/14/22	2.39	Yes
17.	QS 29-37	Shea Blvd / Cholla St	40th St / 44th St	Thin Overlay	10/18/19	Cool Seal	10/12/20	03/14/22	2.40	Yes
18.	QS 2-19	Vineyard Rd / Southern Ave	43rd Ave / 39th Ave	Thin Overlay	10/17/19	Cool Seal	10/23/20	03/14/22	2.41	Yes
19.	QS 11-30	Van Buren St / Roosevelt St	12th St / 16th St	Thin Overlay	10/15/19	Cool Seal	11/06/20	03/14/22	2.41	Yes
20.	QS 26-28	Las Palmaritas Dr / Dunlap Ave	Central Ave / 7th St	Thin Overlay	09/19/19	Cool Seal	11/03/20	03/14/22	2.48	Yes
21.	QS 4-25	Roeser Rd / Broadway Rd	19th Ave / 15th Ave	Thin Overlay	09/04/19	Cool Seal	10/22/21	03/14/22	2.52	Yes
22.	QS 33-18	Thunderbird Rd / Acoma Dr	47th Ave / 43rd Ave	Thin Overlay	11/30/18	Cool Seal	09/03/20	03/14/22	3.29	Yes

No.	Street or Quarter Section	From	To	Major Treatment	Major Treatment Completion Date	Secondary Treatment (* Pre-Treatment)	Secondary Treatment Completion Date	Field Review Date	Yr Since Last Major Treatment	Visible Reflective Cracking
1.	QS 32-40	Sweetwater Ave / Thunderbird Rd	52nd St / 56th St	Thin Overlay	05/01/20	(*Scrub Seal)		03/23/22	1.89	Yes
2.	QS 29-19	Peoria Ave / Cholla St	43rd Ave / 39th Ave	Thin Overlay	04/22/20	(*Scrub Seal)		03/23/22	1.92	Yes
3.	QS 29-20 & QS 30-20	Peoria Ave / Poinsettia Dr	39th Ave / 35th Ave	Thin Overlay	11/04/19	(*Scrub Seal)		03/23/22	2.38	Yes
1.	Utopia Rd	19th Ave	15th Ave	Thin Overlay	05/26/20	(*FAST)		03/23/22	1.82	Yes
2.	Durango St	27th Ave	29th Ave	Thin Overlay	09/19/19	(*FAST)		03/23/22	2.51	Yes
1.	Buckeye Rd	59th Ave	51st Ave	Thin Overlay	10/08/20	(*RAP & ANOVA Rejuvenator)		03/23/22	1.45	Yes
1.	QS 30-18	Cholla St / Cactus Rd	47th Ave / 43rd Ave	Thin Overlay	10/28/19	(*RAP Chip Seal)		03/23/22	2.40	Yes
1.	QS 31-20	Cactus Rd / Sweetwater Ave	39th Ave / 35th Ave	Thin Overlay	07/19/19	(*Chip Seal)		03/23/22	2.68	Yes
1.	QS 31-20	Cactus Rd / Sweetwater Ave	39th Ave / 35th Ave	Thin Overlay	07/19/19	(*RAP Slurry Seal)		03/23/22	2.68	Yes
1.	QS 29-20	Peoria Ave / Lupine Ave	39th Ave / 35th Ave	Thin Overlay	11/04/19	(*SAMI)		03/23/22	2.38	Yes
1.	Osborn Rd	7th St	16th St	Fiber Overlay	04/30/21			03/23/22	0.90	Yes
2.	QS 38-18	Grovers Ave / Union Hills Dr	47th Ave / 43rd Ave	Fiber Overlay	03/26/20			03/23/22	1.99	Yes
1.	QS 30-20	Peoria Ave / Lupine Ave	39th Ave / 35th Ave	Ultra Thin Bonded Wearing Course	11/04/19			03/23/22	2.38	Yes