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Development of performance models to determine effectiveness of flexible pavement preservation using a pavement management system

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Development of performance models to determine effectiveness of flexible pavement preservation using a pavement management system

by

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Major: Civil Engineering (Civil Engineering Materials)

Program of Study Committee:
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Neal Iverson

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

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DEDICATION

I started this journey for myself, I continued this challenge for my wife, and I completed this goal for Delaney.

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ACKNOWLEDGMENTS

The journey of graduate school was not one that I was expecting, or even prepared for. Being blatantly honest, it was the culminating result of a slipping grade in my undergraduate course CE 382: Design of Concretes, where the first half-semester was based on portland cement concrete, and the second half was based on hot mix asphalt. By midterm, my low marks inspired me to sit in the front row for the beginning of Dr. Ashley Buss's lectures. This tiny decision ultimately sparked my interest in asphalt materials to the point of getting her attention through my efforts in the course. Catching me in the hallway later that semester, she suggested the possibility of continuing my education through an assistantship. After a few weeks of deliberation, I accepted this proposal and absolutely do not regret it.

Ultimately, I cannot thank Ashley enough, not only for seeing the potential within me, but for guiding me throughout the entire process. She provided me with the exact skillset that allowed me to start my career exactly where I wanted to. As to the rest of my plan-of-study committee, special thanks goes out to Dr. Christopher Williams and Dr. Vernon Schaefer for teaching multiple civil graduate courses of mine while sparing no lack of detail or information that I can now take with me in my career. Thank you, Dr. Eric Cochran, for your genuine patience with me as I worked under your guidance in the pressure sensitive adhesive study. Rounding out the last chair in my plan-of study committee, thank you Dr. Neal Iverson for teaching the most interesting elective that I have ever taken while at Iowa State University. I quite literally look at the world, or at least its surfaces, differently after learning from you.

My success in the program also stemmed from a fantastic support system, made up of my surprisingly patient wife Megan, my family, and my great friends, Sam and Rachael. There were so many individual moments where all these wonderful people gave me the motivation to complete this significant milestone. To everyone else unmentioned, I hope my expression of gratitude can remain unsaid.

ABSTRACT

More, now than ever, importance on saving materials, time, and money is at the forefront of infrastructure maintenance. Large strides have been made to achieve these goals through the use of pavement preservation. A properly applied preservation method will extend the service life of the pavement, use less materials than a typical overlay or reconstruction, and result in lower construction costs. The presented research evaluates a variety of analytical methods used to model the performance of four different flexible pavement preservation methods, including microsurfacing, slurry sealing, patching, and crack/joint sealing.

Best-fit curves were applied to performance data from the Iowa Department of Transportation's (DOT) pavement management system (PMS) to identify the pavement's current rate of deterioration as well as the pavement's response to the preservation method. These curves were collected across multiple projects of each preservation type, and the initial findings showed microsurfacing to have the longest service life extension, according to the pavement condition index (PCI), with a value of 3.7 years. Patching resulted in a 3.4-year extension, followed by slurry sealing (seals targeting only specific cracking) and crack/joint sealing, with service life extensions of 3.0 and 2.2 years, respectively.

Further evaluation of preservation timing and trafficking levels showed the microsurfacings were often being applied too late, likely a result of an economic-based decision-making governing performance-based decision making. Additionally, a split plot repeated measured statistical analysis significantly reduced the unnecessary variation from on project to the next to identify accurate estimations of true preservation effectiveness. Microsurfacing, slurry sealing, and patching all showed statistically significant improvements in PCI, riding performance, and cracking performance, while crack/joint sealing was the only preservation method shown to improve the project's rutting performance. Lastly, economic analysis was applied to these predictive models to better understand the overall quality supplied by the preservation methods. The most cost-effective preservation method of the four was determined to be crack/joint sealing, followed by slurry sealing, microsurfacing, and patching, in that order. When comparing the costs to the quantity of improvement, however, slurry sealing and microsurfacing were substantially more cost-effective than crack/joint sealing and patching.

CHAPTER 1. INTRODUCTION

1.1 Flexible Pavement Preservation Methods

The moment any given bituminous roadway is placed on the ground, the process of deterioration begins. The quality at that moment cannot be improved without human intervention. The climate, trafficking, binder source, aggregate supply, moisture, and many other variables all play into a complex series of feedbacks that determine the performance of the pavement. To counteract this immediate degradation, multiple flexible preservation methods have been determined, including anything from thin overlays and microsurfacings, to slurry seals and fog seals, and more extreme measures, such as full depth reclamation and cold-in-place recycling (Wu et al. 2010).

The focus of this research centers around four flexible preservation methods, including microsurfacing, slurry sealing, patching, and crack/joint sealing. The average use of microsurfacings and slurry seals is for preventative maintenance, while patching and crack/joint sealing are reactive maintenance by default (Broughton et al. 2012).

Microsurfacings are dense-graded mixtures of aggregate, polymer-modified asphalt emulsion, water, and mineral fillers. Materially, slurry seals are very similar to microsurfacings, but maintain a thinner profile in nature. Typical application methods involve treatment of the entire surface or filling ruts with multiple passes of the construction equipment, and improvements in the pavement's friction, rut depths, and surface cracking are expected (Broughton et al. 2012).

HMA patching involves the removal of severely distressed pavements and replacing the void with a structurally sufficient HMA mixture. This preservation is commonly chosen as a spot-treatment to address only the failed areas of pavements, and can be full-depth, partial depth, or filled potholes, depending on the severity of the distresses (NCHRP 2014).

Crack sealing/filling is one of the most economical and widely performed flexible preservation method. The process involves cleaning out the surface cracks, and then filling them with liquid asphalt binder. Observed success in preventing water infiltration and rate of crack propagation have proven this simple treatment to maintain its effectiveness (Johnson et. al. 2000).

1.2 Performance Expectations

Depending on the extent, location, and test subjects, the expectations of pavement performance often produce wide ranges of service life extensions. Table 1-1 lists the service life extensions determined in the Federal Highway Administration study by Wu et al. for the four preservation methods evaluated in this study (2010).

Table 1-1 *Service Life Extensions for Flexible Preservation Methods (Wu et al. 2010)*

Preservation Method	Service Life Extension
Microsurfacing	3-8 Years
Slurry Sealing	4-7 Years
Patching	NA
Crack/Joint Sealing	0-4 Years

These ranges were based on a six-state involvement in their research, providing broad variety between pavement sections (Wu et al. 2010). Patching is harder to identify the service life extension of primarily due to the relatively low percentage of pavement surface covered by the patches. Addressing the impact on the total structure by means of a small sample set has its challenges, but methods were utilized in this research to meet these challenges. A goal of this research was to determine the local expectations of pavement performance for Iowa-based preservations.

1.3 Pavement Management System

A pavement management system (PMS), also referred to as a pavement management information system (PMIS), can be created for any collection of roadways. The overarching goal of a PMS is to provide the desired pavement performance at the lowest economic cost (Hudson et al. 1979). A recognizable trend across infrastructure-related agencies is the development and use of PMS's to provide better economic decision making.

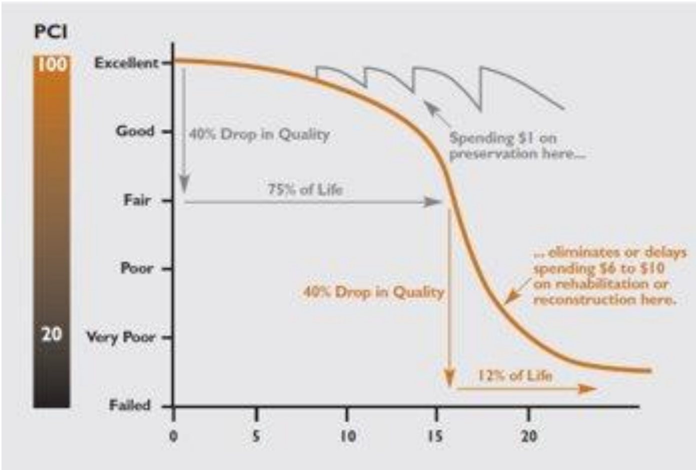

Figure 1-1 *Economic value of preservation compared to rehabilitation or reconstruction (Galehouse et al. 2003)*

A highly referenced figure by Galehouse et. al. shows the economic benefit of earlier preservation timing, compared to later rehabilitation or reconstruction (2003). This figure is presented here as Figure 1-1. Pavement performance indices are easier to maintain at higher levels. Typical agency practices involve more extensive, less routine rehabilitations or reconstructions, while current efforts suggest less extensive, more routine preservations. The economic benefit of a more frequent, but less expensive, preservation can be determined from pavement management system data through various life cycle cost analyses.

1.4 Organization of Dissertation

This dissertation presents the processes involved in taking PMS data, modeling the pavement performance, and evaluating the effectiveness of microsurfacings, slurry seals, patches, and crack/joint seals. The research consists of six chapters as follows:

Chapter 2 lays out the type of information that was extracted from the Iowa DOT's pavement management system. This data focused in on the PCI, rutting, riding, and cracking indices, all of which provide a quality metric for the subset of pavement performance they represent. The method of fitting one of three functions to both the pre-preservation and post-preservation data of a given project's performance index is introduced. The evaluated slurry seal projects are analyzed according to their existing condition and their application type over the first four years post-treatment.

Chapter 3 applies the methods introduced in Chapter 2 to a multitude of microsurfacing projects. These projects are then grouped by trafficking levels to determine any trends between the timing of the preservation and the quantity of traffic on the microsurfaced pavements. Additionally, an evaluation of the four index service life extensions (rutting, riding, cracking, and PCI indices) at varying preservation timings and traffic levels identifies any correlation between the two.

Chapter 4 utilized a split plot repeated measures statistical design to isolate a better approximation of the true relationship between a preserved versus an unpreserved pavement section for all four types of flexible pavement preservation methods. Statistical differences between the average performance of each preservation method and the predictive unpreserved trends, with the removed variation caused by each different pavement section, showed a better picture of the pavement preservation effectiveness.

Chapter 5 takes the collected performance modeling values and applies a life cycle cost analysis to each preservation method. Consideration of sensitive inputs in conjunction with average historical costs, local to the state of Iowa, yielded the comparable value of equivalent annual uniform cost and cost per index value benefit. Lastly, Chapter 6 discusses the primary conclusions of the overarching research effort, wrapping up with recommendations for future research.

1.3 References

Broughton, B., Lee, S., and Kim, Y., 2012. 30 Years of Microsurfacing: A Review. *International Scholarly Research Network*, Vol. 2012, Article 279643.

Galehouse, L., Moulthrop, J. S., Hicks, R. G. 2003. Principles of Pavement Preservation Definitions, Benefits, Issues, and Barriers. *Transportation Research Record*. 228.

Hudson, W. R., Haas, R., Pedigo, R. D., 1997. Pavement Management System Development. *NCHRP Report 215*, Transportation Research Board, Washington, D.C.

Johnson, D., et. al., 2000. Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements. *Transportation Research Record*, 1697, 31-40.

NCHRP, 2014. *Pavement Patching Practices*. National Cooperative Highway Research Program, Synthesis 463. Transportation Research Board. Washington, D.C.

Wu, Z., Groeger, J., Simpson, A., and Hicks, G. 2010. Performance Evaluation of Various Rehabilitation and Preservation Treatments. *Report FHWA-HIF-10-020*, Federal Highway Administration, Washington, D.C.

CHAPTER 2. EVALUATION OF LOCALLY SOURCED PAVEMENT MANAGEMENT INFORMATION SYSTEM ANALYSIS METHODS TO DETERMINE EFFECTIVENESS OF PAVEMENT PRESERVATION: A STUDY ON SLURRY SEALING

Modified from the paper titled "Analytical Methods to Determine Effectiveness of Slurry Seals in Wet/Freeze Climates Using a Pavement Management Information System," currently under peer-review for the Road Materials and Pavement Design journal.

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2.1 Abstract

With increasing economic pressures worldwide, the amount of money spent on pavement preservation needs to become more effectively utilized. Historically, the Long-Term Pavement Performance (LTPP) study has led to data-driven performance expectations for treatments. Pavement management systems (PMS) allowed many to form analytical methods to evaluate pavement performance, from trend fitting to benefit analysis. Taking these methods and applying them to the Iowa Department of Transportation's (DOT) pavement management information system (PMIS) database can determine preservation utility as well as provide expectations of pavement treatments. Thirteen slurry seal projects across the wet/freeze climate of Iowa, U.S.A., were analyzed to determine the service life extensions and yearly benefit for their pavement condition, rutting, riding, and cracking indices. This study aims to provide a framework for future analysis of more preservation treatments and other PMS databases. Understanding local performance of various

preservation methods leads to better pavement management and economically sound decisions.

2.2 Introduction

With increasing economic pressures worldwide, the amount of money spent on pavement preservation needs to become more effective and appropriately utilized. To properly allocate spending on pavement preservation, two general approaches utilizing a PMS (pavement management system) can be used. The first approach involves the prioritizing of need, typically based on the roadway type (arterial, collector, residential, etc), current pavement condition, AADT, and other factors important to the involved agency. However, the second approach involved the understanding of preservation performance based on actual treatments applied with local means and materials. By analyzing past performance data, identifiable trends provide the ability to determine the effectiveness of the treatments.

2.2.1 PMS Database

In a quote from the 1993 AASHTO Guide for Design of Pavement Structures, "Pavement management is an important process at the network level. [...] However, any network level PMS must have some estimate of pavement condition and related pavement performance and cost predictions as a function of time and expected traffic." The takeaway from this quote is the importance of implementation for network level management. Essentially, the difference between a project level PMS and a network level PMS is the ability to predict future pavement behavior based on pre-existing trends seen across many projects, network wide.

Possibly the most well-known PMS database is the LTTP (Long Term Pavement Performance) program. Administered by the Federal Highway Administration, the program was started in 1987 and ran mostly through 1992, with some continued efforts to this day. By taking periodic measurements across more than 2,000 pavement sections, a multitude of information on rigid, flexible, and composite pavements and rehabilitations was made available to determine in-situ pavement performance (Federal Highway Administration [FHWA], 2009).

Many research initiatives have already analyzed the SPS-3 pavement sections of the LTPP program. The goal of these sections was to provide information on the effectiveness of preventative maintenance for flexible pavements. With such a large data set, trends were identified for a variety of pavement preservations across North America and Canada (FHWA, 2009). This study, however, was an effort to apply some of these analytical methods to develop performance curves for slurry seals using state-level PMS database.

The LTPP program used generalized climactic zones to relate pavement sections with similar climate backgrounds. The four zones were designated as dry/freeze, dry/non-freeze, wet/freeze, and wet/non-freeze. The entirety of Iowa is located within the wet/freeze categorization (FHWA, 2003).

2.2.2 Iowa Department of Transportation Computer-Based Information

The Iowa Department of Transportation's (IaDOT) pavement management information system (PMIS) database was the primary source of data used in this study. This PMIS currently contains information from 1998-2017, including project numbers, years of construction, PCI_2 (Updated Pavement Condition Index), rutting index, IRI Index (International Roughness Index), cracking index, and other related pavement information, broken down into individual original smart keys. These original smart keys are unique, 17 digit numbers that identify the given route, system, direction, beginning and ending mileposts, and county that a segment of the primary road system consists of (Iowa Department of Transportation [IaDOT], 2017).

The IaDOT contracts out the collection and input of all measured PMIS data. With such an extensive network of information, the data can have blemishes (IaDOT, 2017). From single, errant values and false zero placeholders to missing categorical data on certain original smart keys, the data quality also played a role in the available slurry seal projects that could be analyzed. This study focused on implementing and evaluating IaDOT's PMIS data for reliable project-to-project performance analysis.

2.2.3 Slurry Seals

A slurry seal is a mixture of asphalt emulsion, fine aggregates, additives (optional), and water that is placed in a single stone thickness to pavement in need of environmental protection, water-proofing, higher friction values, or to correct bleeding (International Slurry Surfacing Association [ISSA], 2010). This simple and cost-effective preservation method has certainly proven its value in published literature over time.

In a study by Hajj, Loria, Sebaaly, Borroel, & Leiva (2011), an attempt to find the ideal time to place a slurry seal over new construction was performed. It was found that when a slurry seal was placed on new pavements, the amount of PCI increase was much smaller than experienced at three to nine years after new construction. While the observed benefit was promising, the PCI value was more likely to drop faster the later it was applied. It was concluded that the average life span of a slurry seal was typically between two to four years (Hajj et al., 2011). More optimistically, an NCAT report on preventative maintenance of asphalt concrete pavements found the typical service life of a slurry seal to range from three to six years (Brown, 1988).

2.2.4 Modelling Trends of Pavement Performance Indices

Seen in a wide range of models, the function of PCI as a function of time has been interpreted differently my many researchers. Often, a curve depicting PCI as a function of time looks like a second, third, or even fourth order polynomial function of the year. Higher-order polynomials, with the right data, can be fit to very accurately reflect the pavement performance. When modelling PCI as a function of time, Hajj et al. (2011) was achieving R^2 values often above 0.9 with many close to 1.0 using a fourth order polynomial function with a data set of more than 11 years.

The swaying factor in the functionality of a high-power polynomial is the quality and quantity of historical data. Unlike the study by Hajj et al. (2011), the Iowa DOT PMIS rarely contains eleven uninterrupted years of historical data prior to construction. To provide a less sensitive model, in terms of small sets of pre-construction data, a reflected, logistic, sigmoidal (RLS) curve was chosen. A curve of this shape is often seen in cost benefit modelling of PCI over time (Galehouse, Moulthrop, & Hicks, 2003).

The strength of an RLS curve is its ability to modify its shape according to need. It can have a negative linear slope, zero slope, or changing slope that is confined within the bounds of zero slope and an undefined slope with only negative slopes in-between. In a paper devoted to the determination of the best curve to fit the compression modulus master curve for asphalt mixtures, a generalized, logistic, sigmoid curve was fit to the data of multiple test specimens with an R^2 of no less than 0.9985 under various conditions (Forough, Nejad, & Khodaii, 2015). Even further from the field of pavements, two United States Department of Agriculture researchers developed the Van Genuchten-Gupta model, a modified sigmoid function, that was utilized to determine crop yields in accordance to the amount of salt present in the soil (Van Genuchten & Gupta, 1993). The Van Genuchten-Gupta model provides a trend similar to pavement deterioration and modification of this model was used to better fit the slurry seal data.

By selective curve fitting, both a “Do Nothing” and “Observed Performance” trend can be determined for a given project’s index. In a study performed by Dong & Huang (2012), a similar approach was performed to the international roughness index (IRI) of various LTPP pavement sections. The “Do Nothing” trend looks at the IRI values prior to construction and fits a function that can then predict post-treatment effects. Similarly, an “Observed Performance” trend fits a function to the data post-treatment. Dong & Huang (2012), then identify the area between these two trends as the observable benefit gained by performing the treatment.

2.2.5 Cost of Preservation vs. Rehabilitation

It is well known that the earlier a pavement receives treatment, the greater the economic advantage can be. The primary difference between pavement preservation and pavement rehabilitation is the desired outcome. Pavement preservations can only be expected to reduce aging and restore serviceability, but pavement rehabilitations also need to increase the pavement’s strength (Geiger, 2005).

The importance of pavement preservation early in a pavement’s life, compared to a rehabilitation, is best explained by Galehouse et al. (2003). The economic value of restoring PCI at different pavement ages is made by analyzing a curve, represented by an RLS function. Due to the initial plateau of the pavement performance curve, followed by a step decline, the report explains that the first 40% in quality lost by a pavement is often over 75% of its service life, while the next 40% is lost in the next 12% of its service life. To restore the pavement back to high PCI values, what would cost one dollar around year 10 could end up costing anywhere from six to ten dollars at 20 years. From 2006 economic estimates, a typical roadway that receives regular preservation treatments can save up to $350,000 (USD) over a 25-year life span, since an untreated pavement would then need to be reconstructed. The $140,000 (USD) to preserve the pavement far outweighs the $490,000 (USD) of reconstruction. (Galehouse et. al., 2003).

2.3 Materials and Methods

Thirteen slurry seal projects completed in the state of Iowa were selected to better understand the benefits, disadvantages, and trends that can be identified through analysis of the Iowa DOT's PMIS database. These thirteen projects consisted of three different slurry seal applications, including center-line sealing, longitudinal crack sealing, and transverse crack sealing.

The PMIS database used in this study includes a very thorough collection of data, but a select few items were taken into consideration. The PCI, Rutting Index, Riding Index, and Cracking Index were all examined as functions of time, in years. Through selective data cleaning, based off sound principles, both a "Do Nothing" and an "Observed Performance" trend-line were fit to these four index values, and the amount of index value improvement, as well as the extension of service lives, was determined for each project.

2.3.1 Slurry Seal Projects and Projects Locations

The thirteen projects completed in the state of Iowa, which were selected for this study, were not based on certain performances or uses, but instead if the project was constructed before 2015, allowing for at least two years of post-slurry seal performance data collection. In Iowa, slurry seals are often strategically applied in targeted areas of the lane and not the entire lane width to address a particular pavement distress. For the thirteen projects in this study, slurry seals were used in the following ways: three projects sealed only the center-line, three projects sealed only longitudinally cracking, five projects sealed only transverse cracking, one project sealed the center-line and longitudinal cracking, and the last project sealed the center-line and transverse cracking. The locations of each project can be seen in Figure 2-1.

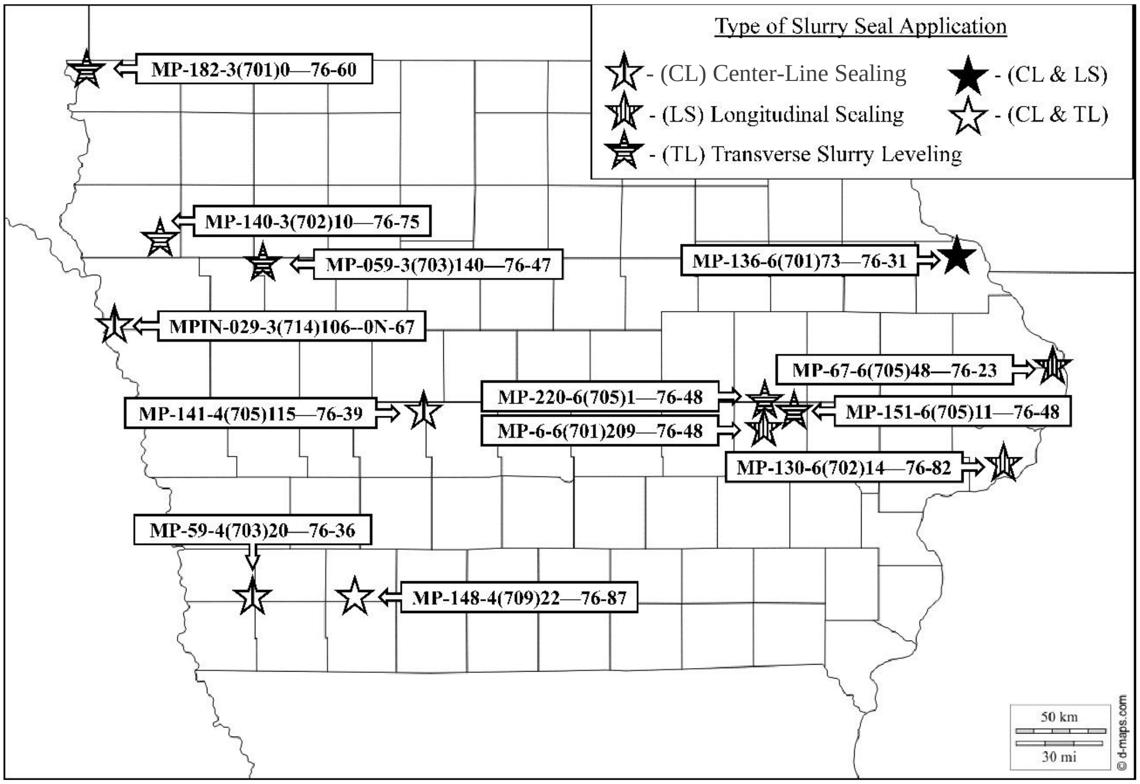

Figure 2-1 *Location and type of slurry seal application of all thirteen slurry seal projects located throughout the state of Iowa (County map from https://d-maps.com/carte.php?num_car=7012&lang=en)*

2.3.2 Methods

The first step in the analysis was to format the Iowa DOT PMIS data in such a manner that comparisons between projects could be made. To do this, the pavement performance data was converted to relative years based on when the slurry seal was applied with the construction year being equal to zero. For example, if a slurry seal project was placed in 2007, the performance data corresponding to 2007 is given the relative age of 0, while 2006 and 2008 performance data has relative years of -1 and 1, respectively. This allows comparison of treatments relative to the year of construction.

Index based trends

With the projects now in a state allowing for comparisons of PCI, the data was examined across all relative years. Based on a study and report from 2014, the Iowa DOT updated their PCI calculation, calculated using an equation weighting cracking, ride and rutting as shown in Equation 1 (Bektas, Smadi, & Al-Zoubi, 2014).

$$PCI\_2 = 0.4 \times (Cracking\ Ind.) + (0.4 \times\ Riding\ Ind.) + (0.2 \times Rutting\ Ind.) \quad (1)$$

PCI assigns a numerical value between zero and 100 that explains the condition of the pavement at the time of measurement, with 100 being the best condition possible. The indices used to calculate PCI are all on a scale of zero to 100, where 100 represents the best condition for each index. The cracking index is a scale that weighs the impact of various observed cracking, furthered explained in Equation 2. The riding index is a scale that weighs the impact of the measured IRI values, where any values higher than 0.5 m/km result in an index value of zero. Lastly, the rutting index is a scale that weighs the depth of wheel-path ruts, where any ruts higher than 12.7 mm result in an index value of 100. For PCC pavements, the faulting index replaces the rutting index.

$$Cracking\ Ind. = 0.2 \times (TCI) + 0.1 \times (LCI) +\ 0.3 \times (L_{WP}CI) +\ 0.4 \times (ACI) \quad (2)$$

Where TCI is the transverse cracking index, LCI is the longitudinal cracking index, $L_{WP}CI$ is the longitudinal wheel path cracking index, and ACI is the alligator cracking index. All indices presented are also on a zero to 100 scale, where 100 represents a pavement with no cracking/distress.

Do nothing trends

Taking a modified approach to that of Dong & Huang (2012), the goal was to determine individual index benefits. To home in on the effect of these slurry seals, each projects PCI data was plotted against their relative years. By identifying steady or downward trends of PCI values up to a relative year of -1, any earlier preservation or rehabilitation could be identified when the PCI experienced a substantial increase. To create a “Do Nothing Trend,” any of these values seen before the closest PCI increase were selectively eliminated since the index value jump was indicative of a different treatment, or related construction method, that was applied to the pavement. The selective elimination removed data that is not directly associated with the deterioration trend prior to relative year zero. A best-fit RLS function modified from a standard logistic sigmoidal function, as seen in Equation 3, was set to the remaining PCI values, as seen in Equation 3.

$$S(y) = \frac{1}{1+e^{-y}} \tag{3}$$

Where S(y) is a standard, logistic, sigmoidal function, and y is the relative year, on the x-axis.

To modify this standard logistic sigmoidal function to best fit the data, three coefficients, a multiplier of 100, and a sign change were added. These modifications were inspired by the RLS function’s utility, described by the Van Genuchten-Gupta model. Figure 2-2 showcases how these changes take effect.

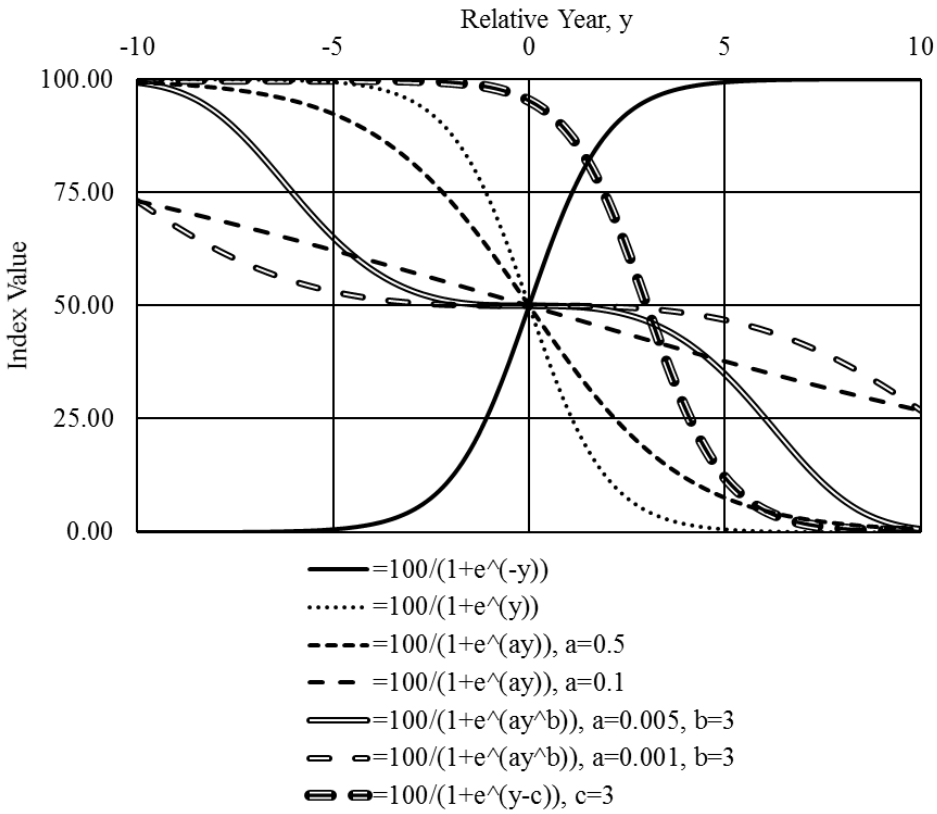

Figure 2-2 *General graph of a sigmoidal curve and how the addition of coefficients can alter the original function*

First, note that all equations now have 100 in the numerator. This caps the function to a highest value of 100 and a lowest value of zero. Next, by changing the negative in front of the relative year, the function is now reflected over the y-axis. The addition of the "a" coefficient forces the function toward linearity between the maximum and minimum values. The "b" coefficient, in the form of an exponent on the relative year, introduces the functions ability to level out around its central inflection point. Many of the fourth-order polynomials presented in the study by Hajj et. al. (2011), displayed a temporary levelling out, that the "b" coefficient can now address. Lastly, by subtracting the coefficient "c" from the exponent of the exponential, the RLS curve can now shift laterally. The resulting function can be seen in Equation 4.

$$RLS = \frac{100}{1+e^{ay^{b}-c}} \quad (4)$$

Where RLS is the reflected, logistic, sigmoidal function, a, b, and c are all coefficients unique to each index value trend, and y is the relative year. These coefficients are determined by minimizing the sum of the squared difference from the predictive "Do Nothing Trend" function created by plotting the remaining index values with their respective relative years.

These "Do Nothing Trend" equations were then extrapolated outward to a distance equal to the largest relative year within each project's data set. If the trend crossed the x-axis, a value of zero was assumed for all remaining relative years. Comparatively, both linear and second-order polynomial functions were best fit to each project's "Do Nothing" data. These functions can be seen in Equation 5 and Equation 6, respectively.

$$Linear\ Function = -by + c \quad (5)$$

$$Second - Order\ Polynomial = -ay^2 - by + c \quad (6)$$

Where a, b, and c are all coefficients unique to each index value trend, and y is the relative year. These coefficients are determined in the same way as those for the RLS. In both cases, the a and b coefficients are restricted to a negative trend, not allowing for pavements to experience improvement when subjected to no treatments over time. While the RLS was capped to values between zero and 100, any values exceeding this range were substituted with either a zero, if negative, or 100, if greater than 100.

Observed Performance Trends

Similar to the "Do Nothing Trend," the identification of any steady or downward trends of PCI values from relative year zero and up allow for the selective elimination of any non-post slurry seal treatment effects on the pavement. In an identical fashion to the "Do Nothing Trends," the trend lines were also fit to individual RLS, second-order polynomial, or linear functions.

Index benefit

With both a "Do Nothing Trend" and an "Observed Performance Trend," the PCI benefit could be calculated for each relative year greater than or equal to zero by taking the definite integral of the difference between both trend equations, as seen in Equation 7.

$$PCI\ Benefit = \int_{y-1}^{y} (BF_{OP.}(y) - BF_{DN}(y))\, dy \qquad (7)$$

Where PCI benefit is a numerical value of PCI difference over the course of the relative year in question, y is the relative year, and $BF_{OP.}(y)$ and $BF_{DN}(y)$ are the best fit functions of the "Observed Performance Trend" and the "Do Nothing Trend," respectively. Figure 2-3 shows an example graphical representation of each relative year's index benefit. Relative year zero's index benefit is simply the difference between the "Observed Performance Trend" and the "Do Nothing Trend", while each year after is the amount of benefit experienced throughout the year.

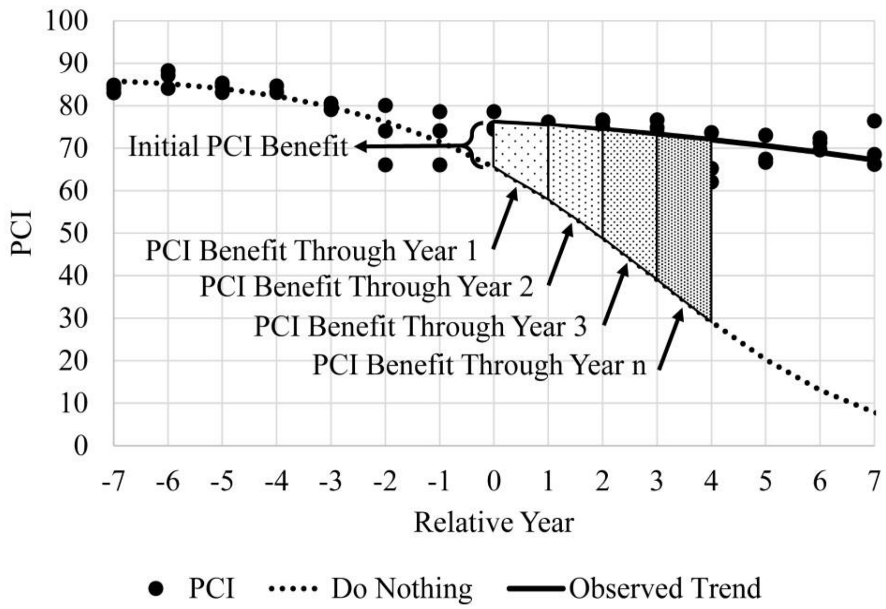

Figure 2-3 *Index value benefit determination*

Index service life extension

In addition to the condition benefit, the service life extension seen from the slurry seal application can also be determined. On a project-to-project basis, the service life extension can be calculated as seen in Equation 8.

$$BF_{OP.}(y) = IV_{DN\ at\ Year\ 0} \tag{8}$$

Where $BF_{OP.}(y)$ is the best fit function of the "Observed Performance Trend" and $IV_{DN\ at\ Year\ 0}$ is the Index Value of the "Do Nothing Trend" predicted for year zero.

By solving for y, the relative year at which the "Observed Performance Trend" falls back to the index value of which it started can be determined. Conceptually, this is explaining the time that it takes the "Observed Performance Trend" to reach a PCI value that would be expected if nothing was done to the pavement at relative year zero, and this interval will be considered the service life extension. Two ambiguous cases can occur when analyzing the data in this manner. In the situation that the "Observed Performance Trend" has a slope of, or close to, zero, the service life extension could unrealistically obtain a value of tens of years, or even infinity. These extensions will be noted, but not further evaluated. In addition, if the "Observed Performance Trend" has a lower index value than the "Do Nothing Trends," there will be no observed benefit, and the service life extension will have a value of zero years.

On a treatment level basis, the service life extension can be estimated by taking all valid service life values from each project's "Observed Performance Trends" and "Do Nothing Trends," and then averaging them to determine the service life extension for slurry seals in general. This value will be compared to individual project service life extension values as well.

Rutting, riding, and cracking index benefits and index service life extensions

"Do Nothing Trends" and "Observed Performance Trends" will estimate actual service life extension for the other three individual indices like the process for PCI life extension. The trends will also allow for the individual determination of rutting, riding, and cracking benefits/year. These will be able to identify the areas where slurry seals have the largest impacts as well as the areas where the impacts are minimal.

2.4 Results

The determined coefficients for each best fit function, as well as all graphs including every data point and graphical fit for each project's four indices can be found in Appendix A.

2.4.1 Index Benefits

To better explain the collected data, the index value benefits throughout each relative year were examined in three scenarios. In the first approach, the values were averaged across all projects. In the second approach, the values were averaged across all projects sharing similar predicted PCI values at relative year zero. The three categories that a project could be assigned were "Good," "Fair," or "Poor," with respective index ranges of 100-75, 74.9-50, and 49.9-0. In the third approach, the benefits/year were averaged across each type of slurry seal application. The two projects that involved two different slurry sealing procedures were included into the average for each application type.

Table 2-1 *Quantity of projects with "Do Nothing" and "Observed Performance" trend data at each relative year from zero*

Relative Year	Number of Projects with Data						
	"Poor" PCI Index	"Fair" PCI Index	"Good" PCI Index	Center-Line Seal	Longitudinal Crack Seal	Transverse Levelling	All Projects
0	4	8	1	5	4	6	13
1	4	8	1	5	4	6	13
2	4	8	1	5	4	6	13
3	4	7	1	4	4	6	12
4	3	7	1	3	3	6	11
5	3	6	0	2	3	5	9
6	3	5	0	2	2	5	8
7	2	1	0	1	1	1	3
8	0	1	0	1	0	0	1
9	0	1	0	1	0	0	1
10	0	1	0	1	0	0	1
11	0	1	0	1	0	0	1
12	0	1	0	1	0	0	1

The information in Table 2-1 displays the rationale for not continuing data analysis four years after slurry seal application. By year five, nearly half of the projects either experienced another treatment effect which significantly raised the PCI values, preventing any further slurry seal related performance trends, or the projects had been placed recently and do not have more than four years of performance trends available.

In approach 1, where the projects index value benefits throughout each relative year were all averaged, seen in Figure 2-4, the first observation was the immediate improvement across all four indices after the slurry seal was applied. The primary observation was the superior performance of cracking index improvement from the slurry sealing compared to the other indices. The cracking index showed a minimum improvement of 14.4, up to 19.1 by relative year three. Referring to Equation 1, although the cracking index benefits were substantial, only limited benefits for the ride quality and rutting indices were recognized after slurry seal application. For this reason, the overall PCI saw a quantity of improvement higher than the rutting and riding indices, but less than the cracking index improvement.

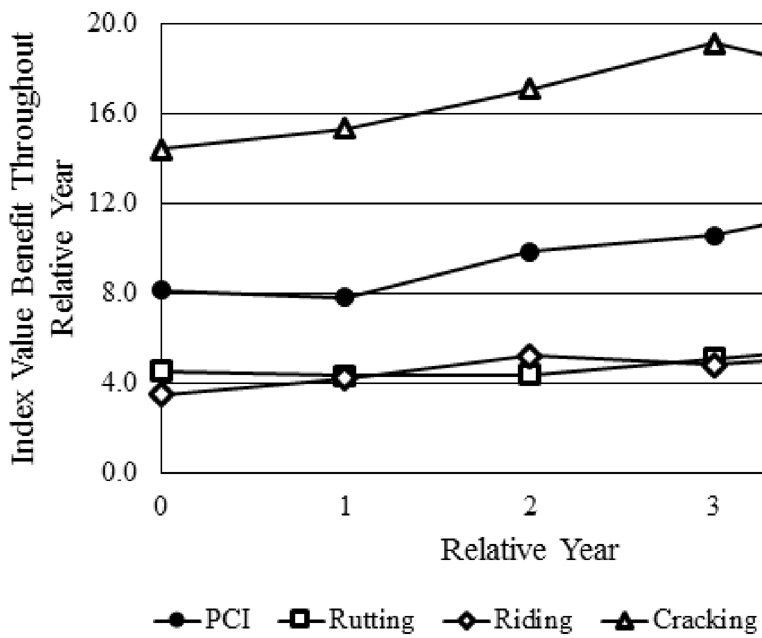

Figure 2-4 *Index value benefits for approach 1*

The data was then broken into good, fair, or poor subset categories based on the predicted roadway condition at the time of treatment application. Figure 2-5, Figure 2-6, Figure 2-7, and Figure 2-8 show the individual index value benefits for each category of “Good,” “Fair,” and “Poor” PCI category, as predicted at relative year zero. It is important to note that there was only one “Good” project, so representation of the “Good” category within these figures is completely based on how the single project performed.

Figure 2-5 shows upward trends of PCI benefit over time for both "Fair" and "Poor" projects. The larger benefit seen for "Poor" projects is evident of the larger room these projects had to improve. Starting at lower PCI values, they have more opportunity to improve their individual pavement condition indices. The single "Good" project did not show any improvement in PCI.

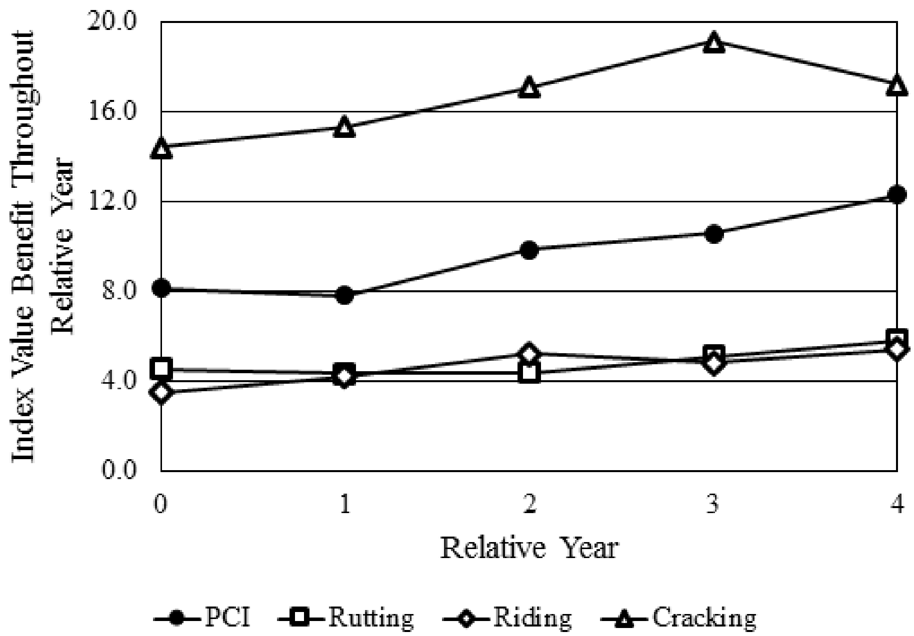

Figure 2-5 *PCI value benefits for approach 2*

When examining the rutting index in Figure 2-6, the "Good" project again showed no slurry seal benefit. However, the "Fair" and "Poor" projects showed a maintenance of the original slurry benefit over the next four years, with benefits of roughly 4 points and 7.5 points, respectively. This shows that while the rate of deterioration of the pavement index remained very similar, the initial rutting benefit can be maintained for at least for years.

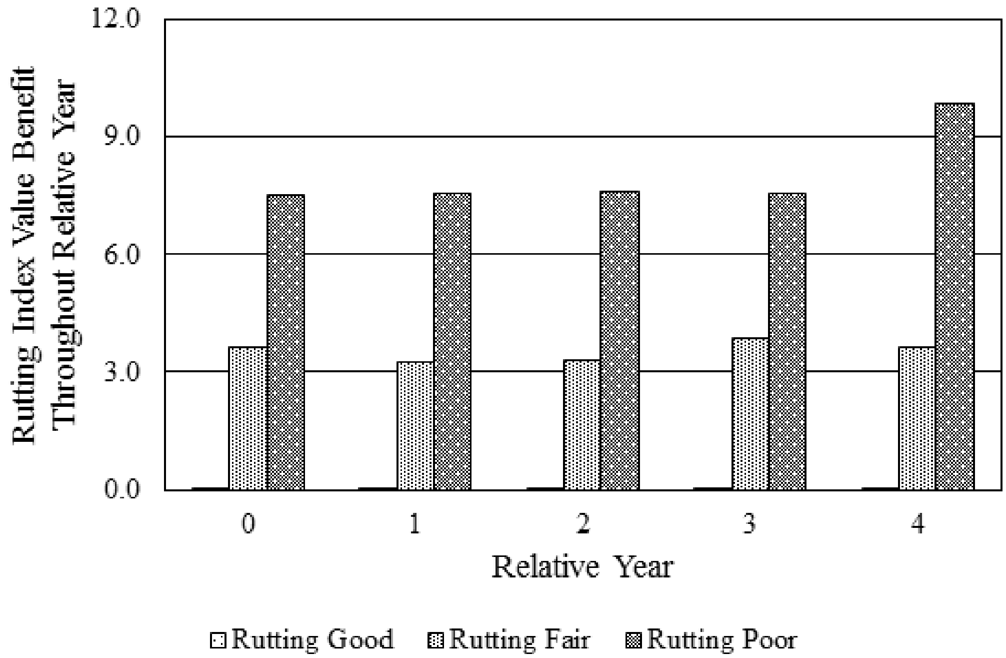

Figure 2-6 *Rutting index value benefits for approach 2*

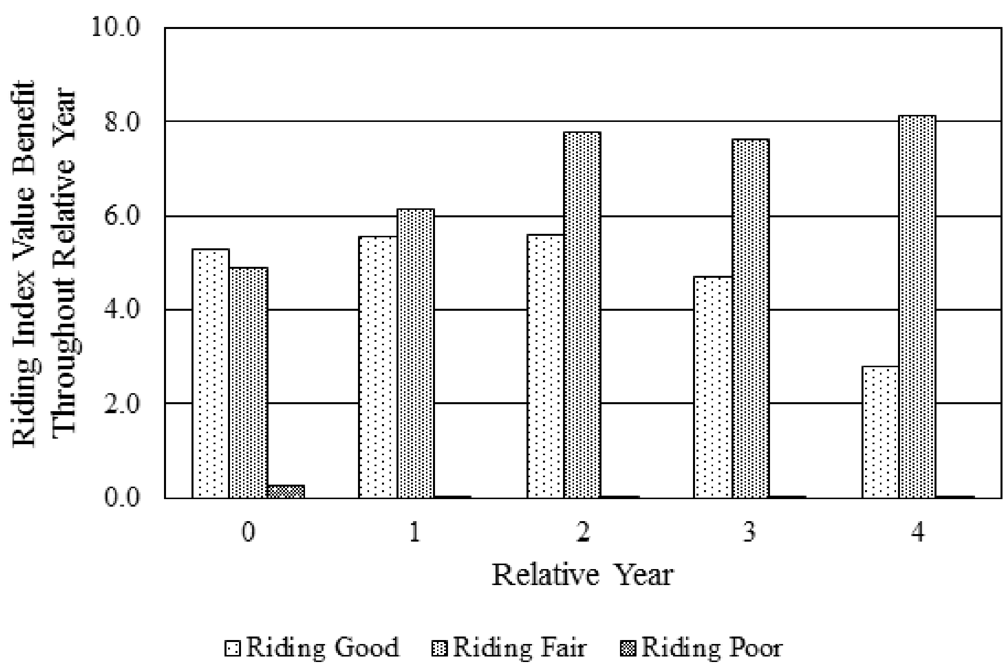

Figure 2-7 *Riding index benefits for approach 2*

Unlike the PCI and rutting indices, the single "Good" projects showed an improved benefit in the riding index. Figure 2-7 shows that an original benefit of 5 to 6 points was maintained for two years but showed signs of decreasing through relative year 4. This shows that the rate of deterioration of the "Observed Performance" trend line was faster than that of the "Do Nothing" trend line. The "Fair" projects also reported similar initial riding index benefits, but these benefits increased over time instead of decreasing. The "Poor" projects observed virtually no improvement in riding index benefit, with the only non-zero value coming in at 0.3 points.

Figure 2-8 shows the cracking index to be substantially different than the other indices. The "Good" project saw an initial benefit just short of 10 points that increased up to 17.2 points by relative year 4. The "Fair" projects showed minimal cracking index improvement with a maintained benefit of approximately 3 points over the first four years. On the contrary, the "Poor" projects observed significant cracking index benefits. The initial index benefit was 37 points, improving to a benefit of 47.1 points by relative year 4. The slurry applications for these "Poor" projects was clearly chosen to remedy the severe cracking at these locations.

When broken down into individual slurry seal application methods for approach 3, further trends were identified, seen in Figure 2-9, Figure 2-10, and Figure 2-11. For longitudinal crack sealing in Figure 2-9, the riding index was virtually unimproved, and the rutting index saw between five to ten points improvement decreasing almost to no benefit by relative year four. The PCI saw an initial benefit of 11.3 points than increased over time to just over 20 points. Similar to approaches 1 and 2, the cracking index showed the largest index value benefit.

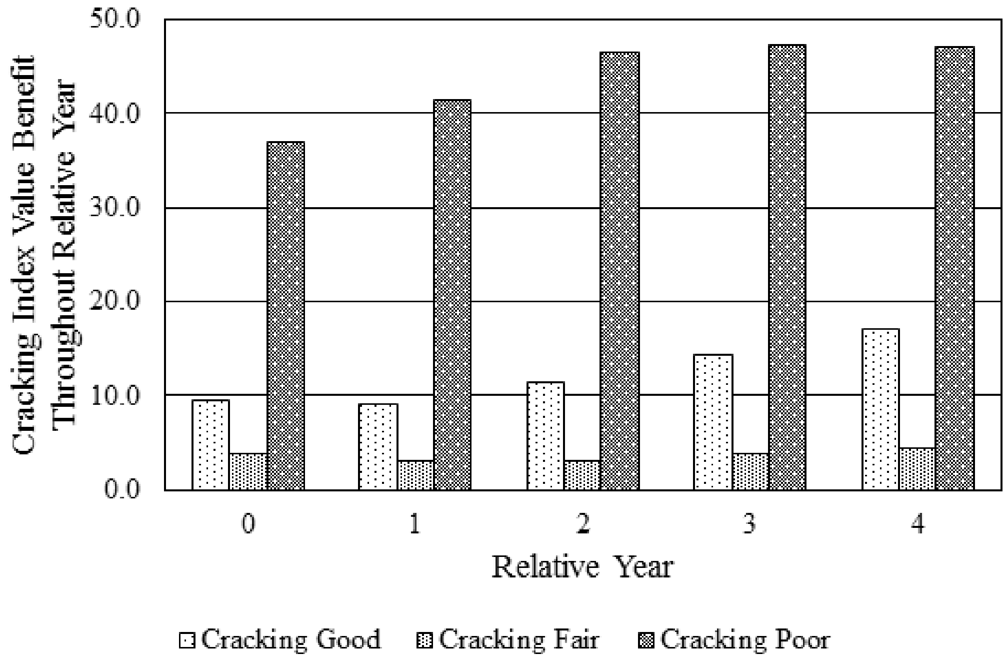

Figure 2-8 *Cracking index value benefits for approach 2*

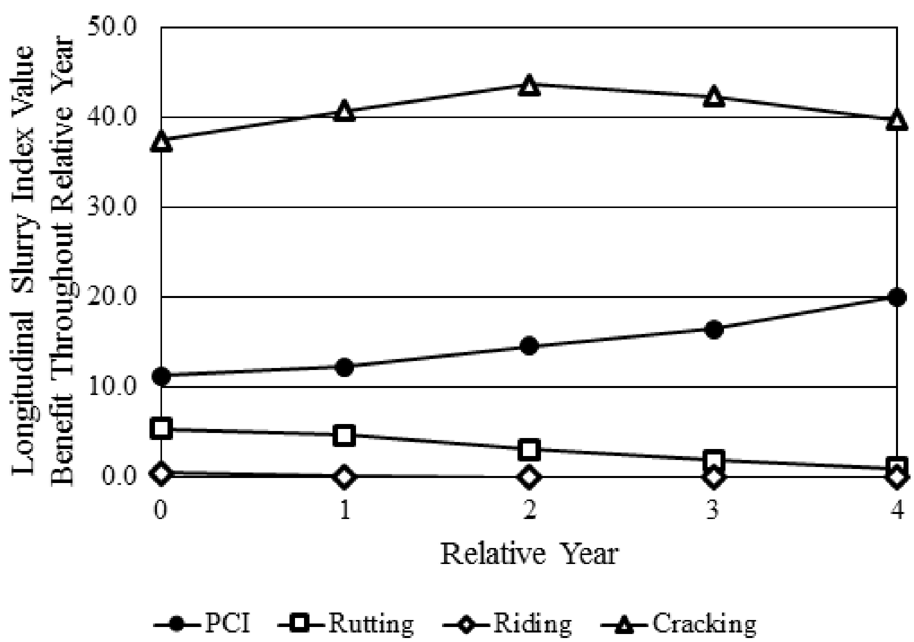

Figure 2-9 *Index value benefits of longitudinal slurry sealing projects for approach 3*

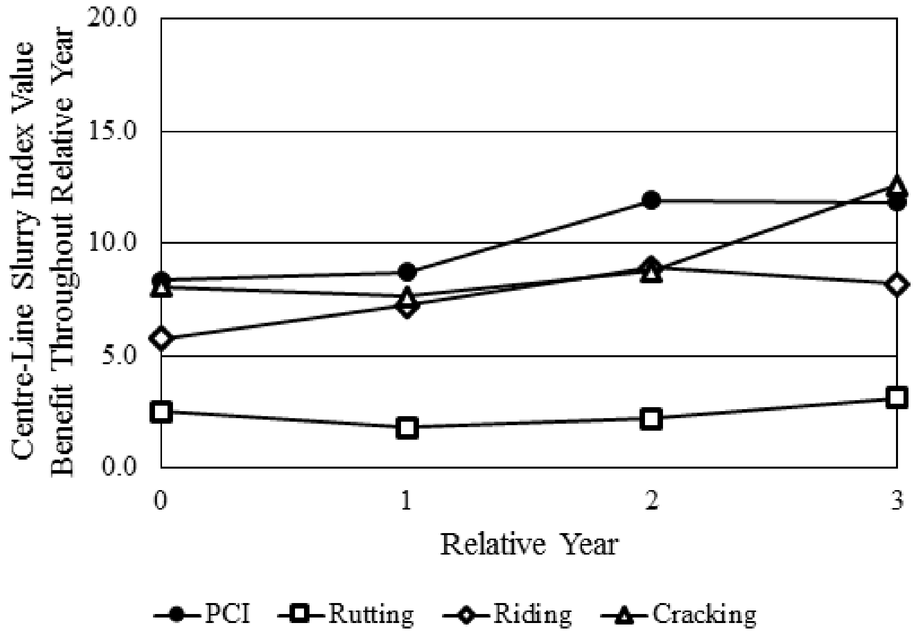

Figure 2-10 *Index value benefits of center-line slurry sealing projects for approach 3*

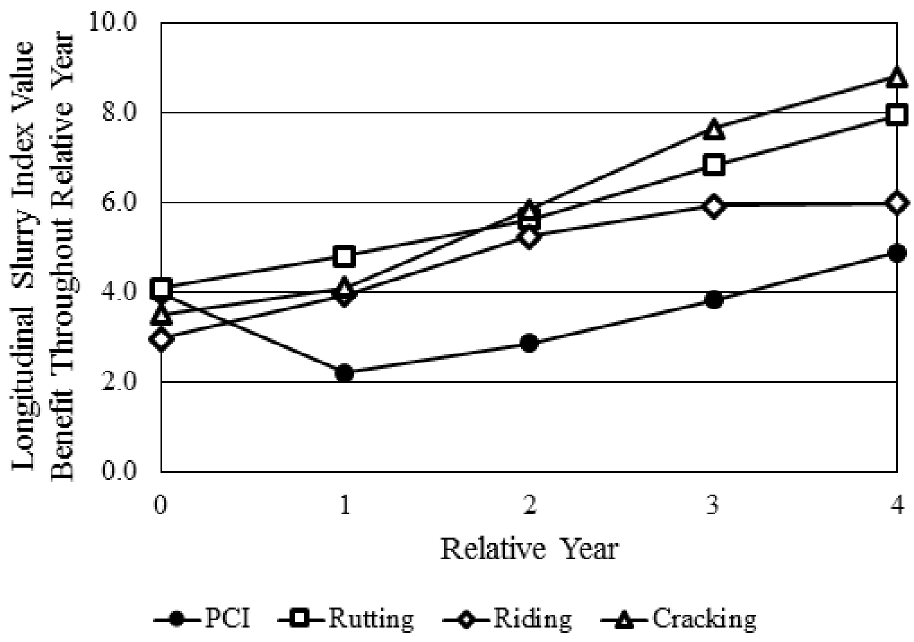

Figure 2-11 *Index value benefits of transverse slurry leveling projects for approach 3*

When the center-line sealing was performed, the PCI and cracking index benefits was the largest initial improvement, and after three years, both indices saw benefits approximately five points higher. The riding index performed similarly but started and finished with benefits about 3 points lower. The rutting index maintained a benefit of about 2 to 3 points from relative year zero to relative year three.

After transverse levelling was performed, as seen in Figure 2-11, an initial benefit improvement of around 3 to 4 points was seen across all four indices. Besides a 1.8-point drop from relative year zero to relative year one in PCI benefit, all four indices showed improvement in benefit after each year. The cracking index saw the largest final benefit with a value of 8.8, while the PCI had a benefit of 4.9.

2.4.2 Service Life Extensions

After a best fit function was set to each project's "Do Nothing" and "Observed Performance" trends, the predicted index value at relative year zero was determined. From here, each project's "Observed Performance" trend equation was solved for length, in relative years, by inputting said index value. The results of these calculations are displayed in Table 2-2.

To remain conservative, any service life extensions greater than 10 years were considered infinite and not included in respective averages. The values in the table will then reflect slightly lower index service life extensions as these large extensions are not factored in. The thirteen projects in total experienced a PCI service life extension of 2.6 years. The rutting and riding indices had shorter service life extensions, while the cracking index produced an equal service life extension, at a length of 2.6 years.

Table 2-2 *Service life extension values for PCI, rutting, riding, and cracking indices*

PCI Category	Slurry Application	Project Number	Index Service Life Extension, Years			
			PCI	Rutting	Riding	Cracking
P	LS	MP-006-6(701)209--76-48	5.0	4.1	0.2	6.5
F	TL	MP-059-3(703)140--76-47	0.4	5.1	2.4	0.0
F	CL	MP-059-4(703)20--76-36	3.6	8.9	0.5	4.9
F	LS	MP-067-6(705)48--76-23	0.3	1.3	0.4	2.3
P	LS	MP-130-6(702)14--76-82	7.8	0.0	0.0	7.2
P	CL/LS	MP-136-6(701)73--76-31	>>10	0.0	0.0	>>10
F	TL	MP-140-3(702)10--76-75	1.6	2.2	3.4	0.0
F	CL	MP-141-4(705)115--76-39	>>10	0.2	>>10	>>10
F	CL/TL	MP-148-4(709)22--76-87	0.0	0.0	>10	0.0
G	TL	MP-151-6(705)11--76-48	0.0	0.0	2.6	>>10
P	TL	MP-182-3(701)0--76-60	0.0	6.2	0.0	5.1
F	TL	MP-220-6(705)1--76-48	7.1	0.0	>>10	0.0
F	CL	MPIN-029-3(714)106--0N-67	>>10	0.0	>>10	0.0
Averages						
Project Quantity		All Projects	2.6	2.2	1.1	2.6
1		"Good" (PCI, 75-100)	0.0	0.0	2.6	-
8		"Fair" (PCI, 50-74.5)	2.2	2.2	1.7	1.0
4		"Poor" (PCI, 0-49.9)	4.3	2.6	0.1	6.3
4		Longitudinal Slurry Sealing	4.4	1.4	0.2	5.2
5		Centre-Line Slurry Sealing	1.8	1.8	0.3	1.6
6		Transverse Slurry Sealing	1.5	2.3	2.1	1.0
Note: (1) >>10 denotes a service life extension exceeding 20 years, service lives greater than 10 years not included in averages. (2) P, F, and G denote "Good," "Fair," and "Poor" PCI categories. (3) LS, CL, and TL denote longitudinal slurry, centre-line slurry, and transverse levelling.						

When the service life extensions were averaged within the "Poor," "Fair," and "Good" PCI categories, the PCI service life for the one "Good" project was zero. The "Fair" projects achieved 2.2 years, and the "Poor" projects achieved 4.3 years of PCI service life extension. The rutting index resulted in equal service life extensions for the "Good" and "Fair" projects, but the "Poor" projects saw less improvement, with 2.6 years. The opposite trend emerges for the riding index, where the one "Good" project resulted in the longest service life extension of 2.6 years, the “Fair” projects achieved 1.7 years, and the “Poor” projects achieved 0.1 years. Much like the PCI service life extensions, it appears that the “Fair” projects see less service life extension than the “Poor” projects, with values of 1.0 and 6.3 years, respectively.

When averaging the types of slurry seal applications, including center-line sealing, longitudinal crack sealing, and transverse crack sealing, longitudinal slurry sealing extended the PCI and cracking service life substantially more than the other two application types, with respective lengths of 4.4 years and 5.2 years. The rutting index and cracking index was most improved after transverse slurry levelling, with service life extensions of 2.3 and 2.1 years, respectively.

While transverse slurry levelling can substantially improve the service life of the riding index, it achieved the lowest service life extensions for PCI and cracking index, with respective lengths of 1.5 and 1.0 years. Center-line slurry sealing is not expected to improve the riding index, but longitudinal slurry also showed minimal improvements to the riding index.

2.5 Conclusions

Using an RLS, second order polynomial, or linear function to develop a pavement performance curve, the index benefit throughout each relative year and the service life extensions for PCI and the rutting, riding, and cracking indices was evaluated for the eleven slurry seal projects. Statistical data from such small sample sets only provide limited results, however, observed trends over multiple projects help to develop expected trends as performance of more treatments becomes available. The following conclusions were made according to the data accessed from the Iowa DOT PMIS database:

In general, slurry sealing can improve the initial PCI of a pavement by 8.2 points and can extend the service life by 2.6 years. The rutting, riding, and cracking indices also showed initial improvements and displayed service life extensions no less than 1.1 years, limited by the riding index. In most fronts, a slurry seal in the climactic background of Iowa should benefit the pavement for at least two years.

For pavements in “Fair” conditions (50<PCI<74.5) at relative year zero, initial improvements were seen across all indices, with the PCI service life expected to be around 2.2 years. The rutting index showed similar results, but slurry seals on these pavements still only improve the riding and cracking quality for about one year.

Pavements in “Poor” conditions (0<PCI<49.9) at relative year zero also show improvements to each index, and their expected PCI service life increases from around 2.2 years up to 4.3 years. Service life extensions for the riding index were virtually non-existent.

Longitudinal applications of slurry sealing not involving the center-line extend the expected service lives of each index by at least 1.4 years, expect for the riding index, where, again, no benefit or service life extensions are seen. The PCI service life extension for this application method was 4.4 years.

Center-line slurry applications show fewer promising results with around 1.8 years of PCI service life extension, with similar results for the rutting and cracking indices. The riding index showed the least benefit over the first four years.

Transverse slurry sealing can be very effective in improving the riding index of a pavement. With the riding index experiencing around a three-point jump in initial benefit, the service life of this index is 2.1 years. However, transverse sealing was shown to expect the shortest PCI service life extension, with a value of 1.5 years.

Often, each index value benefit throughout the previous relative year was either within one index value, or larger, each progressive year. This shows that the progression of each “Observed Performance” trend was less deteriorative than the “Do Nothing” trend. While service life extensions are seen across each index on average, the rate of deterioration is almost always slower, or equal, in speed after slurry seal applications than before the treatment application.

2.6 Discussion

While these conclusions may hold true within this wet-freeze climactic zone throughout the state of Iowa, the small subset of projects and application types almost certainly do not paint a perfectly clear performance of every slurry seal in the state. The above conclusions are made not to be taken immediately at face value, but more accurately as the groundwork for the importance of PMIS analysis. The goal of this study was to take aspects of other research and show potential analytical methods and models used to evaluate pavement performance based on a non-LTPP PMIS database.

While some of these best-fit functions may not be the strongest, a few things need to be remembered. Some performance data provides sporadic trends. This can be attributed to different measurement crews recording data in the field to accidental PMIS data entry. Some of these projects are more of a general, scatter plot than identifiable trends. Additionally, some projects have conflicting original smart key values, and some have up to seven different keys for each project. While trends may appear evident, fitting a least-square RLS, or any function, may result in low R^2 values. Further evaluations could consider looking at trends on a key-to-key basis rather than a project-by-project.

Further analysis on this subject area could include cost-modelling to determine the dollar amount that it cost to add one point in benefit to any of the four indices that were studied. By obtaining accurate project cost data, and then discounting the dollar value back to a relative year of zero, predictions on how economically effective a pavement preservation is could be made.

2.7 References

AASHTO. (1993). Design Related Project Level Pavement Management, *AASHTO Guide for Design of Pavement Structures* (pp. Part I 31-39). Washington, D.C.: American Association of State Highway and Transportation Officials.

Brown, E. R. (1988). *Preventative Maintenance of Asphalt Concrete Pavements*, NCAT Report 88-01. Presented at the Transportation Research Board Annual Meeting.

Dong, Q., Huang, B. H. (2012). Evaluation of Effectiveness and Cost-Effectiveness of Asphalt Pavement Rehabilitations Utilizing LTPP Data. *Journal of Transportation Engineering ASCE*. 138. No 6.

FHWA. (2003). Introduction to the LTPP Information Management System (IMS) [Report]. Retrieved from https://www.fhwa.dot.gov/publications/research/ infrastructure/ pavements/ltpp/reports/ 03088/01.cfm

FHWA. (2009). Long-Term Pavement Performance Program [Brochure]. Retrieved from https://infopave.fhwa.dot.gov/InfoPave_Repository/Reports/A10%20%20 Reports %20and%20Briefs/A10_20%20-%20Resource%20Documents/A10_20_20 %20-%20Brochures/FHWA_HRT-15-%20018.pdf

Forough, S. A., Nejad, F. M., Khodaii, A. (2015). An Investigation of Different Fitting Functions to Accurately Model the compressive Relaxation Modulus Master Curve of Asphalt Mixes. *Road Materials and Pavement Design*, 16, pp. 767-783.

Galehouse, L., Moulthrop, J. S., Hicks, R. G. (2003). Principles of Pavement Preservation Definitions, Benefits, Issues, and Barriers. *Transportation Research Record*. 228.

Geiger, D. R. (2005, September 12). Pavement Preservation Definitions [Memorandum]. Retrieved from https://www.fhwa.dot.gov/pavement/preservation/ 091205.cfm.

Hajj, E. Y., Loria, L., Sebaaly, P. E., Borroel, C. M., Leiva, P. (2011). Optimum Time for Application of Slurry Seal to Asphalt Concrete Pavements. *Transportation Research Record*, 2235, pp. 66-81.

Iowa DOT. (2017). Iowa DOT Open Data. Retrieved from http://data.iowadot.gov/data sets/pmis-2015.

ISSA. (2010). *High Performance Slurry Systems Inspector's Manual*. Annapolis, MD: International Slurry Surfacing Association.

Van Genuchten, M. T., Gupta, S. K. (1993). A Reassessment on the Crop Tolerance Response Function. Journal of the Indian Society of Soil Science, 41, pp. 730-737.

CHAPTER 3. APPLICATION OF ANALYTICAL METHODS TO DETERMINE EXPECTED PERFORMANCE AND IMPACT OF TRAFFICKING AND TIMING ON MICROSURFACINGS

Modified from the paper titled "Microsurfacing Performance Evaluation Using a Locally Sourced Pavement Management Information System," currently under peer-review for the Journal of Transportation Engineering: Part B, Pavements.

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3.1 Abstract

The burden of small budgets and increasing need for economic used of tax-payer money has furthered the desire to understand performance-based behavior of individual pavement preservation methods. The use of the Iowa DOT's state-specific pavement management information system can provide performance behaviors dependent only on local factors. By finding best-fit trends of pre-construction and post-construction for different pavement indices, the service life extensions and index benefits have been determined for 23 different microsurfacing projects. According to the pavement condition index, the average service life extension seen from Iowa microsurfacings is 3.7 years. The rutting, riding, and cracking indices, unique to the Iowa DOT, saw service life extensions of 2.4, 3.3, and 5.3 years, respectively. The condition of the pavement prior to microsurfacing, as well as its AADT value, was found to correlate strongly with the amount of expected index improvement, with higher trafficked pavements performing better than lower trafficked pavements. While application in this study is fixed to microsurfacing treatments, the

framework of analysis can be adapted toward any type of pavement preservation moving forward.

3.2 Introduction

The burden of small budgets and increasing need for economic use of tax-payer money has furthered the desire to understand performance-based behavior of individual pavement preservation methods. The relationship between these methods and their behavior has been studied in great depth over the last few decades. Large initiatives, including the Long Term Pavement Performance (FHWA 2003) study from the Federal Highway Administration (FHWA) and individual state highway agency studies, have taken impressive steps in controlled data collection for extensive analysis of pavement behavior.

By and large, the LTPP study will likely remain the largest nationwide effort to create test sections and monitor how different construction methods result in different performance. To break down climactic regions within the study, the FHWA generalized the continental United States into the categories of wet/freeze, wet/non-freeze, dry/freeze, and dry non-freeze. The state of Iowa falls on the western border of the wet/freeze category that summarizes the entire northwest United States (FHWA 2003). By fitting states into these broad categories, you run into the issue of non-localized, expected performance. Using a smaller geographic scale would promote more reflective performance analysis of a given preservation method.

3.2.1 Pavement Management Information System

By use of the Iowa Department of Transportation's (Iowa DOT) pavement management information system (PMIS), determination of local, Iowa-based pavement preservation performance can be made. With data collection starting in 1998, the Iowa DOT has continued collecting a large quantity of information ranging from pavement structure, traffic data, and pavement condition for all primary roadways. Through use of original smart keys, unique numbers used to identify the route, system, direction, county, and mileposts, project-specific data could be collected by finding all corresponding keys. More importantly, the Iowa DOT makes use of the pavement condition index (PCI), and unique rutting, riding, and cracking indices, all of which are prorated on scales from zero to 100 (Iowa DOT 2017).

Due to 3rd party contracting of the data collection by the Iowa DOT, the publicly-available database can prove inconsistent at times with common ailments consisting of single, errant values, false zeros used as placeholder values, and even missing or uncollected data within certain original smart keys. In a study by Abdelaty, Jeong, and Samdi, it was found that many agencies experience a disconnect data collection and data consistency. Issues ranging from impractical values, time between data collection, and infrequent recordings of in-house maintenance activities can all lead to data inconsistency (Abdelaty, Jeong, and Samdi 2018). Taking careful and frequent measurements could reduce the overall cleanliness of these data sets. After preparing the data by fixing these ailments, implementation and evaluation of the Iowa DOT's PMIS was utilized to determine the performance analysis of microsurfacings within the state.

3.2.2 Pavement Quality Indices

While PCI has been utilized for many years, it's calculation between individual city and state agencies has remained at the discretion of local network needs, and the Iowa DOT is no exception. ASTM D6433 highlights a process of surveying a given pavement section, and then relying on those results to provide deduct values. Based on factors such as alligator cracking, bleeding, rutting, potholes, and more, these deduct values are then used to find corrected deduct values, ultimately leading to the current PCI value (ASTM 2011).

The Iowa DOT had previously relied on PCI calculations dependent on parameters including, but not limited to, age, ESAL service life, International Roughness Index (IRI), friction, and pavement thickness. The currently adopted PCI equation by the Iowa DOT came from a study that fit newly developed indices with appropriate coefficients to match the existing PCI values. For asphalt pavements, these indices are the cracking index, riding index, and rutting index. These indices are all on a scale from zero to 100 and rely on a proportionally prorated system to determine their values.

The rutting index assigns a value of zero to average rut-depth values of 12 mm or greater. No rutting provides a rutting index value of 100. The riding index evaluates any IRI values less than 0.5 m/km as a riding index value of 100, and values greater than 4.0 m/km are assigned riding index values of 0.

The cracking index provides a collective measure of a pavement's transverse cracking, longitudinal cracking, wheel-path cracking, and alligator cracking. Each of these individual cracking distress have their own index with varying thresholds depending on pavement type. For example, a composite road has a threshold of 500 counted transverse cracks per kilometer set to a value of zero for the transverse cracking index, with zero transverse cracks providing a transverse cracking index value of 100. These threshold values are adjusted according to their individual impact on the type of roadway (Bektas, Smadi, and Al-Zoubi 2014). The equation for the cracking index weights the four specific cracking indices as seen in Equation 1:

$$Cracking\ Ind. = 0.2 \times (TCI) + 0.1 \times (LCI) + \ 0.3 \times (WPCI) + \ 0.4 \times (ACI) \qquad (1)$$

Where TCI is the transverse cracking index, LCI is the longitudinal cracking index, WPCI is the wheel path cracking index, and ACI is the alligator cracking index.

The current PCI equation used by the Iowa DOT incorporates the rutting index, riding index, and cracking index in a similar fashion to how the cracking index weights individual indices. The equation for PCI can be seen in Equation 2:

$$PCI = (0.4\ \times Cracking\ Ind.) + (0.4 \times\ Riding\ Ind.) + (0.2 \times Rutting\ Ind.) \qquad (2)$$

3.2.3 Microsurfacing Performance

Microsurfacing is a preservation method that incorporates polymer-modified asphalt that has been emulsified and mixing it with small aggregates, mineral fillers, water, and other chemical or organic additives (Dwight-Hixon and Ooten 1993). Measuring the performance of a microsurfacing can be achieved using a variety of different methods. Often IRI values and rutting values provide initial improvement after the preservation has been applied. Shown to improve IRI values by 0.442 m/km on average and reduce rutting by 4 mm on average, the immediate benefit of a microsurfacing is clearly apparent (Labi, Lamptey, and Kong 2007).

Long term analysis of microsurfacing can provide a clearer image of pavement responses. Service life extensions from microsurfacings have been found to be anywhere from 3-9 years for pavements with sound structure (Labi, Lamptey, and Kong 2007; Erwin and Tighe 2008).

3.3 Materials and Methods

A total of 23 microsurfacing projects across the state of Iowa were evaluated in this study. Determination of their index value benefits and service life extensions through trend fitting of Iowa DOT PMIS data allowed for a collective understanding of how microsurfacings perform within the state of Iowa. While the PMIS database included a multitude of pavement info, limiting the analysis to the four indices, including PCI, rutting, riding, and cracking, allowed for cleaner overall comparisons to be made.

3.3.1 Microsurfacing Projects

Since the PMIS currently has data through 2017, the 23 projects selected in this study were let by the Iowa DOT prior to 2015, allowing for at least two years of post-construction data. Figure 3-1 shows a map of the location for these projects, broken down according to the type of roadway the microsurfacing was placed.

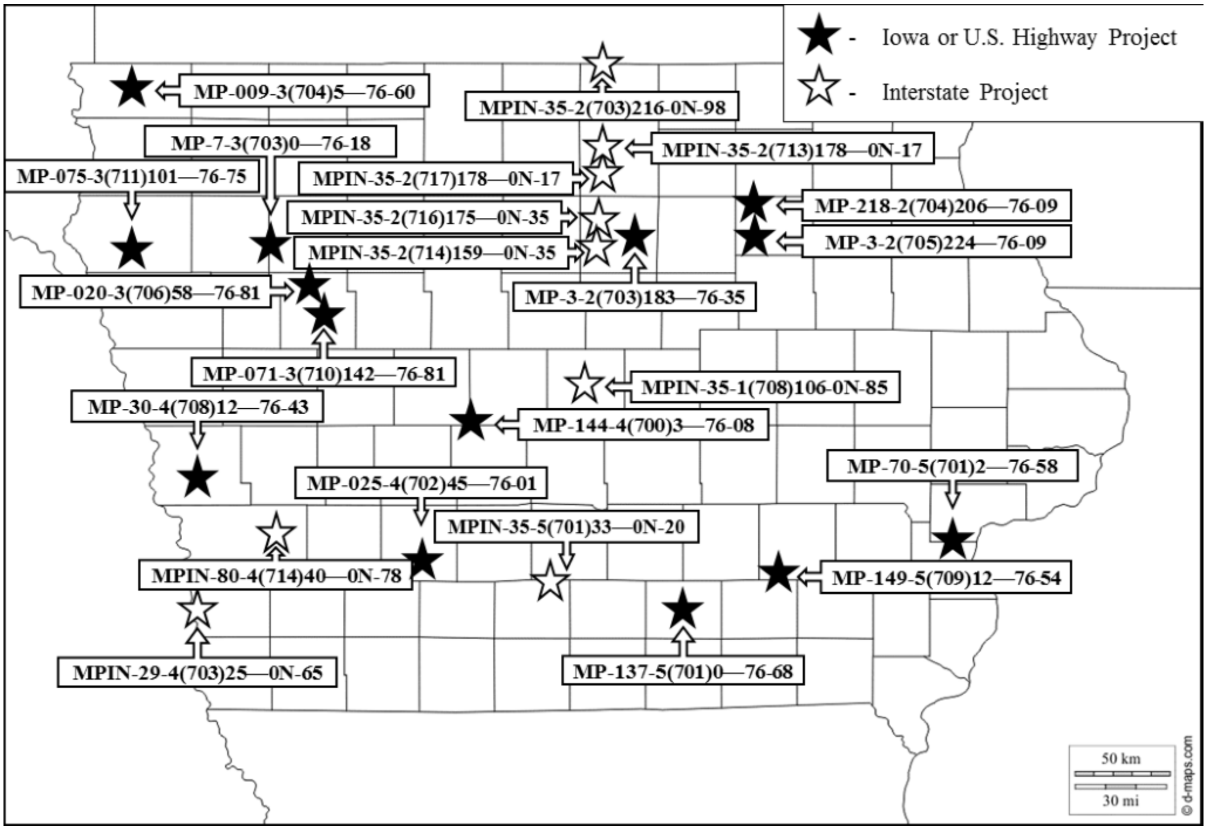

Figure 3-1 *Location of evaluated microsurfacing projects (County map from https://d-maps.com/carte.php?num_car=7012&lang=en)*

With an approximate split down the field with a nine to fourteen ratio of interstate projects to highway projects, an examination of the annual average daily traffic (AADT) and percentage of truck traffic, seen in Table 3-1, shows a fairly even split down the field if the projects are broken out according to AADT values less than or greater than 10,000 vehicles.

With both the US Highway 71 and 75 projects having very high AADT values, this shift provides twelve projects with AADT values less than 10,000 vehicles and eleven projects with AADT values greater than 10,000 vehicles.

Table 3-1 *AADT and percentage of truck traffic for microsurfacings*

Project Name	Route Location	AADT	% Trucks
MP-003-2(703)183--76-35	Iowa Highway 3	2105[a]	14 %
MP-003-2(705)224--76-09	Iowa Highway 3	3390[a]	11 %
MP-007-3(703)0--76-18	Iowa Highway 7	3920[a]	8 %
MP-009-3(704)5--76-60	Iowa Highway 9	3238[a]	11 %
MP-020-3(706)58--76-81	US Highway 20	2040[a]	20 %
MP-025-4(702)45--76-01	Iowa Highway 25	1726[a]	11 %
MP-030-4(708)12--76-43	US Highway 30	5764[a]	16 %
MP-070-5(701)2--76-58	Iowa Highway 70	1556[a]	9 %
MP-137-5(701)0--76-68	Iowa Highway 137	3933[a]	19 %
MP-144-4(700)3--76-08	Iowa Highway 144	1865[a]	12 %
MP-149-5(709)12--76-54	Iowa Highway 149	2301[a]	9 %
MP-218-2(704)206--76-09	US Highway 218	8183[a]	20 %
MP-071-3(710)142--76-81	US Highway 71	13036[b]	12 %
MP-075-3(711)101--76-75	US Highway 75	13100[b]	15 %
MPIN-029-4(703)25--0N-65	Interstate 29	11777[b]	27 %
MPIN-035-1(708)106--0N-85	Interstate 35	29871[b]	15 %
MPIN-035-2(703)216--0N-98	Interstate 35	16200[b]	30 %
MPIN-035-2(713)178--0N-17	Interstate 35	15050[b]	25 %
MPIN-035-2(714)159--0N-35	Interstate 35	14400[b]	23 %
MPIN-035-2(716)175--0N-35	Interstate 35	15400[b]	23 %
MPIN-035-2(717)178--0N-17	Interstate 35	15600[b]	23 %
MPIN-035-5(701)33--0N-20	Interstate 35	19987[b]	25 %
MPIN-080-4(714)40--0N-78	Interstate 80	20700[b]	35 %

[a] Denotes projects with AADT<10,000, [b] Denotes projects with AADT>10,000

3.3.2 Evaluation Methods

Before comparisons of these projects can be made, determination of both index service life extensions and initial index value improvements for each project across all four pavement indices, including the PCI, rutting index, riding index, and cracking index must be calculated.

First, the PMIS data for all project relevant original smart keys must be set to a similar time scale. By setting the year of the microsurfacing treatment to a relative year equal to zero, the data prior to the preservation then counted backwards with negative relative year values and data post-preservation counted forward with positive relative year value. This step created a uniform time scale for all 23 projects. Projects with multiple original smart keys display multiple data points for each relative year of data, creating similar, yet clustered, segments of data.

The next step in the procedure involved fitting trends to the pre-construction data and the post-construction data. The deterioration of the four indices for either of these trends was approximated by minimizing the sum of the squared error with any one of the following three equations.

$$Linear\ Function: \quad Index\ Value = -by + c \tag{3}$$

$$Second\ Order\ Polynomial\ Function: \quad Index\ Value = -ay^2 - by + c \tag{4}$$

$$Reflected\ Logistic\ Sigmoidal\ Function: \quad Index\ Value = \frac{x}{1+e^{ay^b-c}} \tag{5}$$

Where a, b, and c are coefficients solved for in attempt to minimize the sum of the squared error, y is the relative year, x sets the maximum value for the reflected logistic sigmoidal function, and the index value is the value between 0 and 100 for any given index.

The three coefficients for any of the aforementioned functions allowed for significant flexibility when minimizing the sum of the squared error using a spreadsheet software. The linear function allows for a no-slope solution, where “b” equals zero and “c” sets the height at any given time or a linearly decreasing slope when “b” is solved for any positive value, made negative by the sign in front. The second order polynomial can behave in the same manner if the “a” coefficient equals zero. However, when the value of “a” is made negative by the sign in front, this already linearly decreasing curve with increase its rate of index deterioration. By keeping the “a” and “b" coefficients for the linear and second order polynomial functions restricted to negative values, the slope of the index deterioration could not trend upwards.

Similarly, the “a,” “b,” and “c” coefficients for the reflected logistic sigmoidal function allow for straightening and mid-span stepping of the trend. The use of this curve shape was seen in a soil salinity versus crop yield study by Van Genuchten and Gupta. As salinity increased from zero, there was minimal initial impact on yield. After substantial salinity was added, a sudden decrease in yield was observed, but after so much salt, the amount of lost yield was capped to 100 percent (Van Genuchten and Gupta 1993). Pavement deterioration curves similar in shape have been seen across literature. In a study on pavement preservation, a curve, developed by Galehouse, Moulthrop, and Hicks, of PCI versus pavement life depicts a nearly identical shape as that of Van Genuchten’s and Gupta’s (Galehouse, Moulthrop, and Hicks 2003). The “a” coefficient controls the degree of curvature for the overall curve, with smaller values shifting the curve towards linearity. The increase of a mid-span step was added by the “b” coefficient to reflect possible behaviors seen in a study of PCI values over time associated with slurry sealing (Hajj, Loria, Sebaaly, Borroel, and Leiva 2011). Lastly, the “c” coefficient allows the curve to shift left or right across the relative year axis.

All three of these equations were set up to meet the assumption that pavements will not improve without human intervention. After freeze-thaw cycling, high temperature fluctuations, moisture infiltration, and other aging parameters barrage a pavement, the best possible scenario of deterioration behavior is when the index maintains its current performance.

When fitting these functions, significant construction before or after the microsurfacings can impact the quality of fit. Figure 3-2 shows an arbitrary example of how performance jumps from construction interference at relative years -4 and 7 create data points that would skew the actual pavement deterioration behavior. Another important thing to note from this figure is how the data prior to the microsurfacing is only used to create a one year extrapolative prediction as to how the pavement most likely would have performed without receiving a microsurfacing.

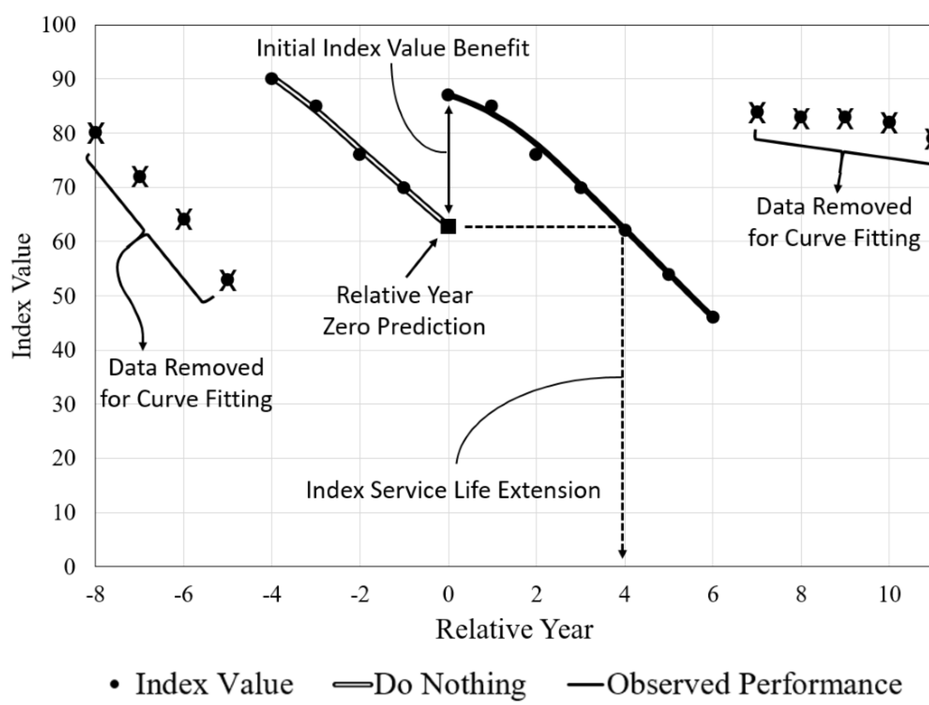

Figure 3-2 *Example explanation of trend line fitting to index value*

Once the pre-construction and post-construction trends have been determined, two different methods were utilized to evaluate the effectiveness of the 23 microsurfacing projects. The first method to evaluate effectiveness includes quantifying the initial index value benefit observed for each pavement index, which includes PCI, rutting, riding and cracking indices. As shown in Figure 3-2, the initial index value benefit is defined as the increase, or decrease, in index condition calculated by taking the value of the post-construction trend minus the prediction of the pre-construction trend at relative year zero. Positive values indicate index improvement, or benefit, while negative value represent a continued deterioration, regardless of the microsurfacing benefits. By plotting the index values prior to the microsurfacing on the x-axis and the amount if index improvement on the y-axis, grouping of the highway projects and interstate projects can be evaluated.

The second method to evaluate effectiveness examines the length of each index's service life extension, defined in this study as the length of time required for the post-construction trend to reach the value equal to relative year zero prediction of the pre-construction trend, also illustrated in Figure 3-2. Two things to note for these service life extensions are as follows: (1) the condition of the index prior to the microsurfacing sets the value of the index as the condition used to evaluate the service life extension, (2) the coefficients used to fit models to the data sometime fit curves with little or no slope, resulting in excessively long service life extensions if data were to be extrapolated, and (3) if the post-construction trend has a lower value than the pre-construction prediction at relative year zero, the service life extension is considered to be zero.

3.4 Results

3.4.1 Comparing Pre-Construction Index Values to the Amount of Observed Improvement

Figure 3-3, Figure 3-4, Figure 3-5, and Figure 3-6 were developed to compare initial pavement condition with the quantity of index improvement for the pavement condition, rutting, riding and cracking pavement indices, respectively. The project data was grouped for projects with less than 10,000 AADT and projects greater than 10,000 AADT. After determining any index value improvement statistical outliers, defined as any points exceeding 1.5 times the interquartile range, linear approximations were fit to the remaining data points. The R^2 values are clear indications that these trends are sensitive to the high variability seen across these 23 projects. An analysis of individual origin keys for projects containing more than one was considered. However, when broken down individually, the variability within the data introduced from a variety of possible sources, led to many trends behaving irregular to the expected performance. As discussed previously, impractical values, time between data collection, and infrequent recordings on in-house maintenance work are some of many sources of user-created variability. When all the original smart keys are curve fit on one graph, the overall R^2 may decrease, but the appearance of typical pavement deterioration emerges. Regardless, these graphical trends can provide insight to what determines the success of a microsurfacing.

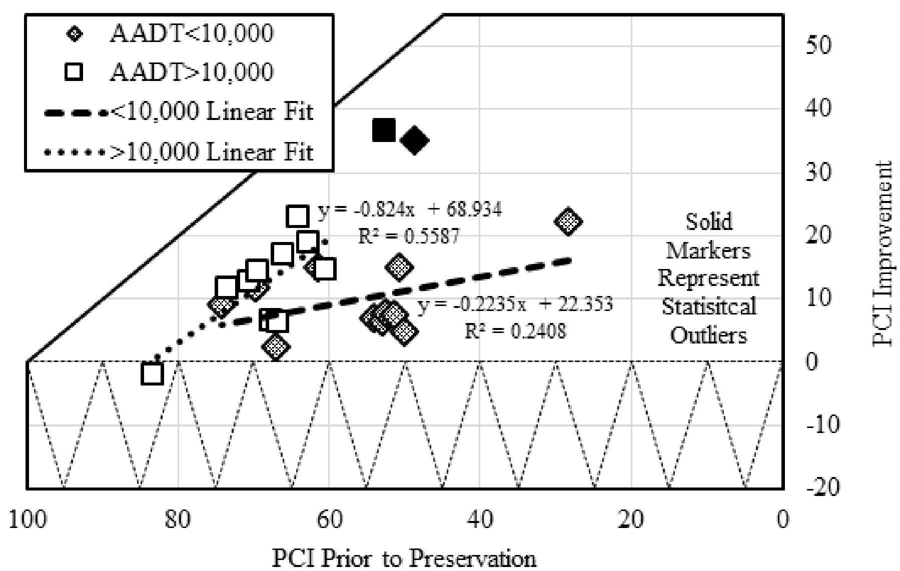

Figure 3-3 *PCI improvement after microsurfacing*

The performance data in Figure 3-3, show negative slopes that vary greatly between the AADT values less than and greater than 10,000. These negative slopes appear to trend upwards, due to the reversed x-axis values. What these tell us is that the projects starting with lower PCI values are seeing larger improvements than those starting with higher values. Part of this is limited by the amount any given project actually can improve. For example, a project starting with a PCI of 80 can only improve 20 points, until the index is fully restored to a value of 100. This is represented by the angled graph border.

With an R^2 of 0.56, the projects with AADT values greater than 10,000 appear to have a fairly linear relationship where every ten point drop in pre-construction PCI value corresponds to an expected improvement of just over 8 points. Meanwhile, the projects with AADT values less than 10,000 are more scattered, resulting in approximately two to three points of improvement for every ten-point drop in pre-construction PCI.

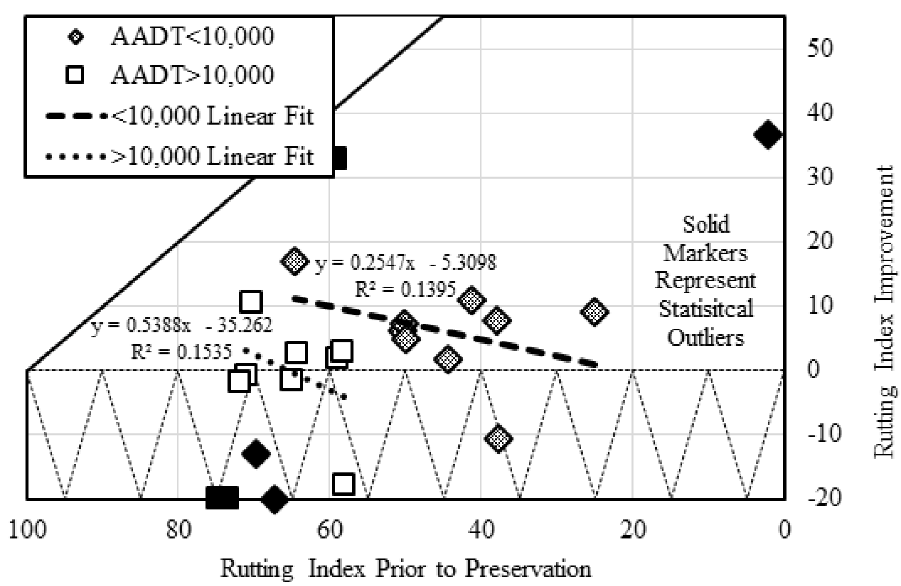

Figure 3-4 *Rutting index improvement after microsurfacing*

Another observation to note is the time at which pavement with AADT values greater than 10,000 are receiving microsurfacings compared to pavements with less than 10,000 AADT. On average, the AADT greater than 10,000 projects were treated with microsurfacings when the PCI was at 68.5, while the AADT less than 10,000 projects received microsurfacings when the PCI was 55.6, more than 10 points lower. The two trends show how this later microsurfacing produces lower quality improvement to the PCI.

Unlike the trends seen with the PCI improvements, the rutting index trends in Figure 3-4 have positive slopes. While still excluding the outliers, determined by values exceeding 1.5 times the interquartile range, there is a distinct grouping between the microsurfacing projects placed on roadways with different traffic levels. An important step back from this analysis is to understand that there are more confounding factors within the pavement design process for pavements with larger AADT values. Higher trafficking will require better materials, and better materials will address the likelihood of corrective rutting for microsurfacings. For projects with AADT values greater than 10,000, for every ten-point drop in pre-microsurfacing rutting index value, a drop of over five points in improvement can be expected. The projects with AADT values less than 10,000 can expect a drop at almost half of the rate to those over 10,000.Both the projects with AADT values above and below 10,000 show trends indicating smaller improvements in the rutting index as the pre-microsurfacing rutting index values decrease. This likely indicates sub-grade or sub-base structural issues that this thin preservation method cannot correct.

It should be noted that there were three projects that far exceeded the threshold of -20 in rutting index improvement. In these three situations, the microsurfacing provided no improvement to the rutting index, as the pavement rutting continued after the preservation method was applied.

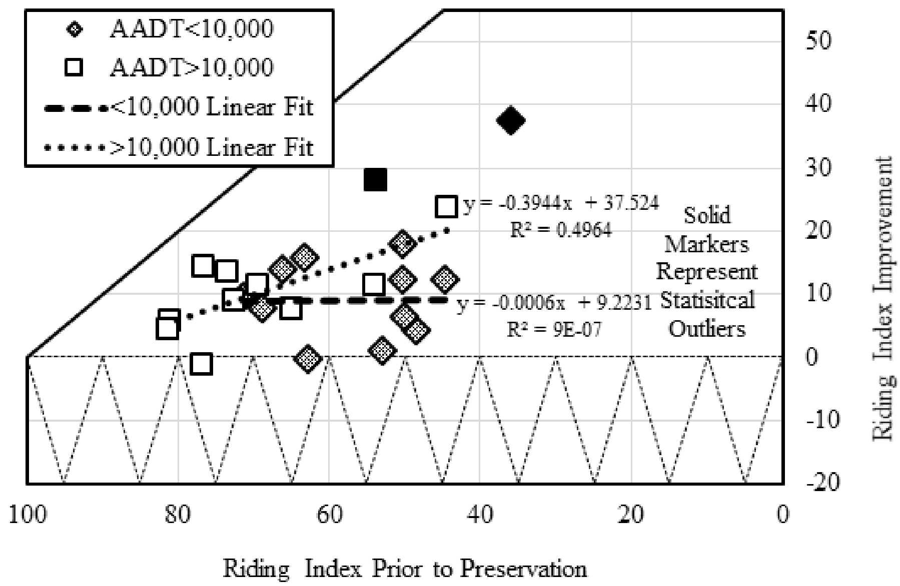

Figure 3-5 *Riding index improvement after microsurfacing*

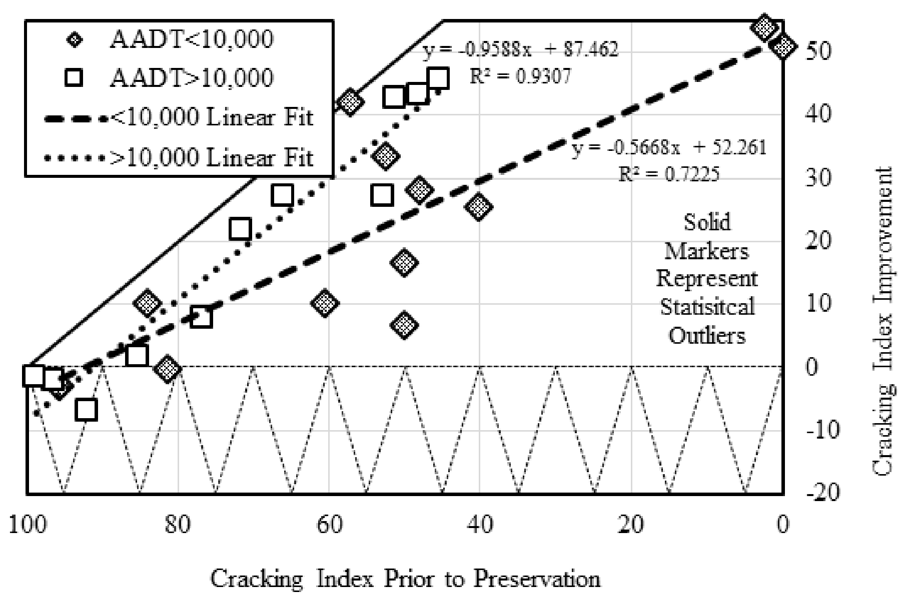

Figure 3-6 *Cracking index improvement after microsurfacing*

The riding index trends, Figure 3-5, show projects with AADT values greater than 10,000 display a loosely linear trend that reflects approximately four points on riding index improvement for every ten point drop in pre-construction riding index value. However, the projects with AADT values less than 10,000 have a trend with an R^2 of virtually zero. Since the slope of this line is virtually non-existent as well, it appears that the expected improvement of these projects is independent of the pre-construction riding index value. With a very widespread on the graph, the typical behavior of projects with AADT values less than 10,000 is harder to predict.

The cracking index improvements, seen in Figure 3-6, are unlike any of the three previous index-based graphs. The observed values displayed a much larger range, resulting in a larger interquartile range that produced no statistical outliers. The other main difference is the inherent lack of separation between projects with AADT values less than and greater than 10,000.

Like the PCI improvement, seen in Figure 3-3, both trends have negative slopes. The projects with AADT values greater than 10,000 have substantially higher R^2 value of 0.93 and predict an improvement of almost one-to-one for every drop in pre-construction cracking index value. The projects with AADT values less than 10,000 still show an increase of almost six points for every ten-point drop in pre-construction cracking index value, although the R^2 value is lower, coming in at 0.72.

While the projects with AADT values less than 10,000 are more scattered, the projects with AADT values greater than 10,000 show an almost full restoration of the cracking index because of the microsurfacing. This is indicative that this preservation is being selected appropriately as a cracking-distress remediation.

3.4.2 Graphical Examination of the Service Life Extensions for Each Pavement Index

Seen in Figure 3-7, the service life extensions, defined as the length of time required for the post-construction trends to reach the relative year zero predicted value of the pre-construction trends are plotted across each of the four evaluated pavement indices. Jittering of the data points has been performed to better display overlapping points.

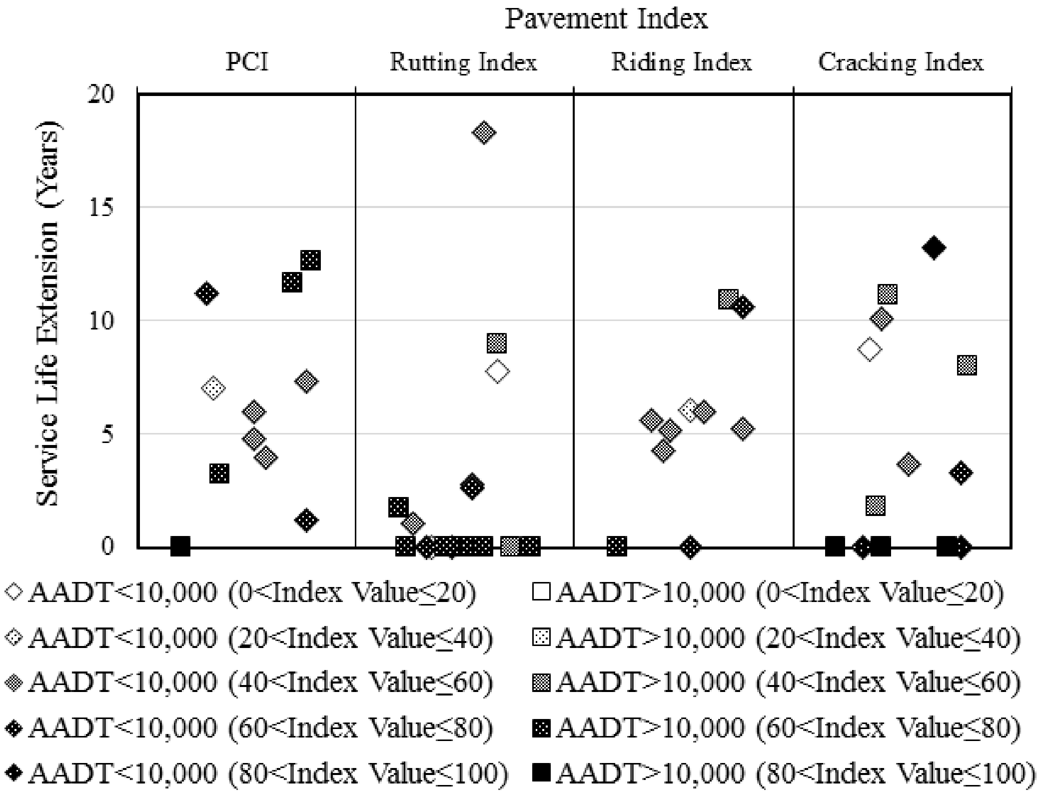

Figure 3-7 *Service life extensions for each pavement index*

Several projects were omitted in the graph due to having flat performance trends after microsurfacing placement; in other words, no deterioration of the microsurfacing was observed. Two reasons were identified for the flat performance trends, first the microsurfacing had not been in place for long or another construction activity, such as paving, occurred shortly after the microsurfacing resulting in a limited number of performance observations and the observations did not provide enough time to begin substantial deterioration.

Second, the darker the square, the higher the pre-construction index value was. A tight grouping of darker data points can be seen along the line of no service life extension. These projects had less room to improve within their respective indices, making it harder for the microsurfacing to raise each index. As a result, the performance trend after microsurfacing was equal to, or lower than, the performance trend for the pavement before the microsurfacing was placed.

Lastly, many these projects were performed on pavements with very low pre-construction index values, anywhere from zero to 60. However, more of these projects were performed on roads having AADT values less than 10,000. With 23 projects and four indices each, 48 indices were of projects with AADT values less than 10,000, and 44 indices were of projects with AADT values greater than 10,000. Figure 3-7 shows 44 of these indices had pre-construction values less than 60, and 32 of those 44 belonged to projects with AADT values less than 10,000. This seems appropriate when considering that less vital roads are more likely to receive less attention. With fewer traveling vehicles on average, lower index values can be sustained when compared to projects located on highly traveled interstates and highways.

Table 3-2 *Summary table of service life extensions*

Project Number	Index Service Life Extension PCI	Rutting	Riding	Cracking
MP-003-2(703)183--76-35	1.2	5.8[a]	3.9[a]	0.0
MP-003-2(705)224--76-09	3.6[a]	7.8	1.9[a]	4.0[a]
MP-007-3(703)0--76-18	4.8	2.6	6.1	3.7
MP-009-3(704)5--76-60	4.0	4.7[a]	6.0	10.0[a] *
MP-020-3(706)58--76-81	2.8[a]	4.1[a]	2.4[a]	10.0[a]*
MP-025-4(702)45--76-01	1.9[a]	5.1[a]	4.3	10.0[a]*
MP-030-4(708)12--76-43	7.4	6.9[a]	5.2	3.3
MP-070-5(701)2--76-58	1.7[a]	0.0	5.2	6.5[a]
MP-071-3(710)142--76-81	1.6[a]	0.0	2.9[a]	0.0
MP-075-3(711)101--76-75	3.5[a]	1.9[a]	5.9[a]	3.2[a]
MP-137-5(701)0--76-68	1.1[a]	1.1	0.3[a]	2.6[a]
MP-144-4(700)3--76-08	7.1	0.0	5.7	8.8
MP-149-5(709)12--76-54	6.0	2.8	0.0	9.9[a]
MP-218-2(704)206--76-09	2.2[a]	0.0	3.4[a]	0.0
MPIN-029-4(703)25--0N-65	2.8[a]	0.0	3.7[a]	8.6[a]
MPIN-035-1(708)106--0N-85	3.1[a]	0.0	2.8[a]	0.7[a]
MPIN-035-2(703)216--0N-98	0.0	1.7	0.0	0.0
MPIN-035-2(713)178--0N-17	4.5[a]	0.0	1.1[a]	10.0[a]*
MPIN-035-2(714)159--0N-35	3.2	1.3[a]	3.6[a]	1.8
MPIN-035-2(716)175--0N-35	3.4[a]	0.0	2.2[a]	10.0[a]*
MPIN-035-2(717)178--0N-17	4.1[a]	0.0	1.4[a]	8.0
MPIN-035-5(701)33--0N-20	8.7[a]	9.0	6.9[a]	10.0[a]*
MPIN-080-4(714)40--0N-78	5.5[a]	0.0	1.9[a]	0.0
Average	**3.7**	**2.4**	**3.3**	**5.3**

[a]Denotes index service life extension recalculated using a straight-line deterioration curve
*Denotes recalculated index service life extension capped at a maximum of 10 years

To obtain index service life extensions for each of the four indices, a linear decline in performance was applied to projects with infinite service life extensions to include these zero-slope trends. To provide a more general understanding of the microsurfacing behavior, the delineation between AADT values was ignored, allowing for more values to be included in the linear decrease. First, the average initial index value benefit divided by the service life extension for all projects without infinite service life extensions was determined to represent the average index value drop per year. By then taking the initial index improvements for the projects with infinite service life extensions and dividing by the average index value drop per year, new index service life extensions are determined. Any recalculated values greater than ten years were capped at a value of ten based on the largest extension seen within current literature. Table 3-2 shows the calculated index service life extensions for each of the four indices.

3.5 Conclusions

This paper displays the process and analysis of microsurfacing projects performed on the State of Iowa's highway network to determine the initial benefit, and service life extension for pavement condition index, cracking index, ride index and rutting index. These indices are unique to the Iowa DOT and incorporate zero to 100 scales with pre-defined thresholds, where certain rutting depths, IRI values, and quantity of cracks result in index values of zero. The PMIS data for each section of the 23 projects was first collected and filtered. From updating older PCI values to the most current Iowa DOT PCI equation, to recognizing errant values and false zeros, the data was then ready for comparison. After adjusting each microsurfacing to a relative year zero, with pre-construction data and post construction data represented as negative and positive relative years, respectively, all of the data could then be evaluated for trend fitting.

By fitting the best of three different equations, including linear, second-order polynomial, and reflected logistic sigmoidal, to each of four pavement indices accepted and determined by the Iowa DOT, clear pre-construction and post-construction trends were determined. These two trends became the basis for evaluation of initial index improvement and index service life extension for each pavement index.

The original jump from the expected pre-construction index value at relative year zero, to the value of the post-construction index value provided the pavement's improvement in overall quality (PCI-based), roughness (IRI-based), rutting (rut-depth-based), and cracking (individual crack index-based). The service life extension for each of the four indices was determined by the time for the post-construction trend's index value to fall back to the predicted pre-construction index value at relative year zero.

Table 3-3 *Expected index improvement after microsurfacing*

Index	AADT	Estimated Improvement for Every 10 Point Drop in Pre-Treatment Condition
PCI	<10,000	2.4
	>10,000	8.3
Rutting	<10,000	-5.4
	>10,000	-2.5
Riding	<10,000	0.0
	>10,000	3.9
Cracking	<10,000	5.7
	>10,000	9.6

When microsurfacing projects were categorized by roadways with AADT values less than and greater than 10,000, certain behaviors were observed. Table 3-3 breaks down the expected index improvements for both projects with AADT values less than and greater than 10,000.

All positive values represent the pavement responding with larger improvements as the index value prior to construction get lower. With none of these values being larger than ten, the pavements in better original condition are still achieving higher index values after the microsurfacings. The two negative values seen for the rutting index show that pavements with worse rutting index values prior to the microsurfacing are less likely to benefit from the treatment. This likely is a result of sub-grade or sub-base structurally related issues. When the pavement structure is demonstrating serious rutting distresses, a thin surface coat of asphalt emulsion and aggregate is not going to provide an adequate structural fix.

Overall, the microsurfacings resulted in a PCI service life extension of 3.7 years, a rutting index service life extension of 2.4 years, a riding index service life extension of 3.3 years, and a cracking index service life extension of 5.3 years. With expectations ranging from three to nine years, it appears that these microsurfacings are being chosen at non-ideal times, resulting in the minimum service life expectation (Labi, Lamptey, and Kong 2007; Erwin and Tighe 2008). With many of these projects occurring when these indices are below a value of 60, the use of a preservation method over a rehabilitation method likely indicates economic-based decision-making governing performance-based decision making.

3.6 Discussion

These analytical tools are not limited to the PCI, rutting, riding, and cracking indices presented in this study. Any pavement distress that is measurable on a continuous number scale could be fit with appropriately bounded equations to predict the pre-treatment and post-treatment condition. Three equations were utilized in this study, but there is also no limit to the creativity of varying deterioration models that could be utilized. The overarching goal was to demonstrate the effectiveness of applying a variety of methods to a unique database to extract performance-based behavior. Both the database and methods can, and should, be adapted to the specific situation.

By now understanding the immediate and long-term benefits of microsurfacings within the State of Iowa, the opportunity for more selective agency decision making can lead to decreased construction costs and longer lasting pavement sections. With a method to sieve out the desired information, such as service life extensions and index value benefits, the possibilities of conducting a life cycle cost analysis, cost-benefit analysis, or other agency-specific analysis is now within reach.

3.7 References

Abdeblaty, A, Jeong, D, and Smadi, O, “Barriers to Implementing Data-Driven Pavement Treatment Peromance Evaluation Process.” Journal of Transportation Engineering, American Society of Civil Engineers. Volume 144, Issue 1. March 2018.

ASTM (2011) “Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.” *D6433*, ASTM, Philadelphia, Pa.

Bektas, F, Smadi, O, Al-Zoubi, M. “Pavement Management Performance Modeling: Evaluating the Existing PCI Equations.” INTRANS Project 13-455, Iowa DOT Project SPR RB14-013. December 2014.

Dwight-Hixon, C., and Ooten, D. A. (1993). “Nine years of microsurfacing in Oklahoma.” Transportation Research Record. 1392, Transportation Research Board, National Research Council, Washington D.C., 13–19.

Erwin, T. and S.L. Tighe, “Safety Effect of Preventive Maintenance: A Case Study of Microsurfacing,” Transportation Research Record: Journal of the Transportation Research Board, No. 2044, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 79–86.

Federal Highway Administration (FHWA) (2003). “Introduction to the LTPP Information Management System (IMS)”. <https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/reports/03088/index.cfm> (Nov. 17, 2018).

Galehouse, L., Moulthrop, J. S., Hicks, R. G. (2003). Principles of Pavement Preservation Definitions, Benefits, Issues, and Barriers. Transportation Research Record. 228.

Hajj, E. Y., Loria, L., Sebaaly, P. E., Borroel, C. M., Leiva, P. (2011). Optimum Time for Application of Slurry Seal to Asphalt Concrete Pavements. Transportation Research Record, 2235, pp. 66-81.

Iowa DOT. (2017). Iowa DOT Open Data. <http://data.iowadot.gov/data sets/pmis-2015> (Mar. 9, 2017).

Labi, S, Lamptey, G, and Kong, S, “Effectiveness of Microsurfacing Treatments,” Journal of Transportation Engineering, American Society of Civil Engineers. Volume 133, Issue 5. May 2007.

Van Genuchten, M. T., Gupta, S. K. (1993). A Reassessment on the Crop Tolerance Response Function. Journal of the Indian Society of Soil Science, 41, pp. 730-737.

CHAPTER 4. RETROSPECTIVE SPLIT-PLOT REPEATED MEASURES STATISTICAL ANALYSIS TO ISOLATE THE IMPACT OF PAVEMENT PRESERVATION

Modified from the paper titled "Retrospective Split-Plot Statistical Analysis to Determine Pavement Preservation Performance," currently under peer-review for the International Journal of Pavement Engineering.

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4.1 Abstract

Understanding of pavement performance is essential to the success of a preservation program, leads to effective spending, and ultimately extends the life span of a given pavement section. With the use of the Iowa Department of Transportation's (DOT) pavement management system (PMS), evaluation of four different types of flexible pavement preservation, including microsurfacing, slurry sealing, patching, and crack sealing/filling, according to their pavement condition index (PCI), rutting, riding, and cracking performance over time. With best-fit trends modelled to describe a project's actual performance and predicted performance, these measured performance indicators were retrospectively applied to a split-plot repeated measures (SP/RM) statistical analysis. By using SP/RM analysis, the extremely high variability between the different pavement sections is more appropriately allocated, and a more accurate estimation of the pavement's response to the preservation can be observed. This abounding analysis provides benefits that are explained in conjunction

with the full analysis of the entirety of the data to provide insight to objectively finding performance benefits of using these flexible pavement preservation techniques.

4.2 Introduction

Pavement performance is becoming a large factor for infrastructure management. Many agencies have implemented repeated data collection across their governing jurisdiction to mixed success. The implementation of the collected data is important to achieving a successful pavement preservation program, reduce overall expenditures, and increase the service lives of the pavements (Galehouse et. al. 2003).

Since 1998, the Iowa DOT had collected extensive information across its entire primary roadway system. This data set includes identification information, structural performance, distress measurements, traffic data, and more (Iowa DOT 2017). A 2014 report for the Iowa DOT evaluated the previous PCI equation, and implemented the use of three unique pavement indices, denoted as the rutting index, riding index, and cracking index, that share weight in the current PCI values (Bektas et. al. 2014). Similar to PCI, these indices are all set to a scale of zero to 100 and provided a convenient means to model critical aspects of the pavement performance.

4.2.1 Performance Modelling

Previous methods to evaluate pavement performance have relied heavily on PCI and International Roughness Index (IRI) values in the past. With IRI values shown to provide reliable and accurate measurements over time, fitting models to IRI data is often seen. A common approach to determining the benefit of a pavement treatment is to fit some curve to the data prior to the treatment and then extrapolating that trend forward in time. With the actual measurements after a treatment are known, a linear trend fit to these data points provides a boundary condition to compare to the extrapolated trend. Dong et al. (2012)

defined these trends as pre-treatment and post-treatment, respectively. The drop in IRI values from the treatment provide an area of benefit that can be numerically quantified (Dong and Huang 2012).

A study on applying IRI as a predictor of asphalt condition found success with a power model that utilized two fitting coefficients but warned that IRI alone should not be a predictor of PCI (Park et. al. 2007). This philosophy was already implemented by the Iowa DOT because Iowa's PCI equation, Equation 1, relates to three different sources of pavement performance, including the rutting, riding, and cracking indices, as seen in Equation 1 (Bektas et. al. 2014).

$$PCI = 0.4 \times (Cracking\ Ind.) + (0.4 \times\ Riding\ Ind.) + (0.2 \times Rutting\ Ind.) \quad (1)$$

Where the cracking, riding, and rutting indices are also on scales of zero to 100, with the rutting index prorated from the average rut depth value, the riding index prorated from IRI values, and the cracking index prorated from a conglomerate of individual cracking distress indices. The coefficients were determined according to the strength of correlation to the original PCI values.

Other functions, such as fourth order polynomials, in one study, have been fit to PCI values to determine optimal timing to apply slurry seals. Many of the performance curve models resulted in very strong R^2 values, proving again that curved functions can accommodate more diverse pavement deterioration characteristics more variation (Hajj et. al. 2011).

4.2.2 Statistical Modelling and Comparisons

The benefit of using an SP/RM design allowed this observational study to objectively procure relevant performance data from a non-randomized, but unbiased, selection process. A typical SP/RM accounts for multiple treatment level effects, split into whole-plot and subplot factors. Simple SP/RM models require at least one of each, where the subplot factor represents the repeated measures taken over time (Cobb 2014).

A detailed example of this analysis comes from a study where dynamic modulus test results were compared using an SP/RM analysis to compare control hot mix asphalt (HMA) and experimental warm mix asphalt (WMA) samples as well as other factors which included reheated/non-reheated plant-collected samples, and moisture conditioned/non-moisture conditioned samples. The whole-plot factor, often called the between-subject factor, was whether the mix was HMA or WMA. The subplot factors, also called within-subject factors were whether the mix was reheated/non-reheated as well as moisture conditioned/non-moisture conditioned. Each asphalt mix was tested at multiple temperatures and frequencies during dynamic modulus testing.

The SP/RM was able to assign more of the variation within the test results to each of the treatment effects and their interaction effects. Unlike a typical ANOVA, this type of analysis separates the error differently. With the blocking of experimental units, the random (or chance) error that naturally occurs is covered by the experimental units instead of the treatments. In this study, the asphalt mixtures account for more of the variation, allowing for better estimations of the treatment and interaction effects (Buss et al. 2018).

4.2.3 Flexible Pavement Preservation Methods

A wide variety of pavement preservation methods exist as a result to large advances in research and industry. The methods evaluated in this study were microsurfacing, slurry sealing, patching, and crack sealing/filling. Microsurfacings are thin slurries constituent of aggregates, polymer-modified asphalts, water, chemical/organic additives, and mineral fillers (Dwight-Hixon and Ooten 1993). While not as robust as an HMA overlay, microsurfacings are effective at temporarily correcting surface distresses and they provide a new wearing surface. Slurry seals are like microsurfacing but are applied in a single stone thickness for the purpose of providing a pavement with environmental protection, higher friction, or waterproofing (ISSA 2010). Correcting surface distresses and improvement to pavement condition is possible, but not to the full extent of a microsurfacing, based on preservation thickness alone.

HMA patching involves the removal of severely distressed pavements and replacing the void with a structurally sufficient HMA mixture. This preservation is commonly chosen as a spot-treatment to address only the failed areas of pavements, and can be full-depth, partial depth, or filled potholes, depending on the severity of the distresses (NCHRP 2014). The patching can completely restore the PCI to a value of 100, but the long-term success of a patch is often predetermined by the failure mechanism that caused the original pavement to fail, i.e. lack of drainage, poor subgrade, lack of edge support, or high trafficking. Additionally, patches are often lower density than the original flexible pavements, which increases the permeability of the patch. Even brand new HMA patches are determined a low-severity distress, according to the Federal Highway Administration's (FHWA) Long Term Pavement Performance (LTPP) distress identification manual (FHWA 2014).

Crack sealing/filling is one of the most economical and widely performed flexible preservation method. The process involves cleaning out the surface cracks, and then filling them with liquid asphalt binder. Observed success in preventing water infiltration and rate of crack propagation have proven this simple treatment to maintain its effectiveness (Johnson et. al. 2000).

4.3 Materials and Methods

4.3.1 Materials

The materials selected for this study are all flexible pavement preservation projects let by the Iowa DOT. In total, 23 microsurfacing, 13 slurry seal, 29 hot mix asphalt patching, and 31 crack sealing/filling projects were examined. The selection process of these projects was not performed via randomization, but instead based on lists of completed Iowa DOT projects that occurred between 1998 and 2015 where useful PMS data could be generated. This timeframe represents the currently available data to develop performance trends within the Iowa DOT's PMS database. If the project had relevant data, with at least two years of post-treatment, it was included, without bias, into the study.

4.3.2 Methods

Determination of index value benefits

Analysis of the Iowa DOT's PMS included the method of taking the collected PCI, rutting index, riding index, and cracking index data, and then fitting pre-treatment and post-treatment performance trends. Both the pre-preservation and post-preservation trends were represented by linear, second-order polynomial, or reflected-logistic sigmoidal functions, where the function with the lowest sum of squared error after solving for coefficients was deemed the best fit. The pre-preservation trend modelled the performance of the pavement from either the beginning of the data collection in 1998 or from the last pavement treatment, identified by significant increases in overall PCI, up to the year prior to the preservation treatment. The post-preservation trend modelled the performance from the time of treatment until the next pavement treatment, also identified by significant increases on overall PCI, or until the current data collection year or 2017.

From this performance trend fitting, the index value benefits across each of the four indices were determined. To obtain the index value benefits, the pre-preservation trends are projected using a model to estimate the pavement's performance as if no preservation treatment had been applied to the pavement. These projections are based on pre-treatment data and known typical deterioration curves for each pavement structure. These projections are made at relative years zero, one, and two, which represent the year that the pavement received preservation and the two years following that preservation, respectively. The use of relating the time of preservation to a relative year zero created a comparable baseline across all analyzed pavement sections.

Limitations of traditional ANOVA for analysis of pavement preservation

Analysis of Variance (ANOVA) is a statistical model used to estimate error and variance within a data set. Outside of taking simple averages to compare one effect with another, the uncertainty in the overall mean's true value means that unknown error needs to be properly measured. The addition of the entire statistical model's estimated effects provides a fitted value, that when subtracted from the observed value, provides an estimated error value. Equation 2 shows how residual error are the result of measuring a sample (Cobb 2014).

$$Observed\ Number = True\ Value + Residual\ Error \tag{2}$$

Where observed number is the measured value from an experimental unit, true value is the actual result of whatever is being measured over the entire population, and residual error is the difference of the true value and observed number.

Regardless of the model setup, mean square values are calculated for error and treatment. The mean square error (MSE) represents the variance experienced within the body of data, while the mean square treatment (MST) represents variance between defined groups within the data. Multiple MST values can be tested within the same model, and the setup of the model determines how the variance is explained. The division of MST values by the appropriate mean square value is defined as an F-Ratio.

The F-Ratio is based upon the right-skewed F-distribution commonly utilized within statistics, and its shape is determined by the degrees of freedom used for the treatment effect divided by the degrees of freedom that remained to estimate the error. In these models, the degrees of freedom are values associated with the number of experimental units, whole-plot, and sub-plot factors. The area remaining under the distribution to the right of any given F-Ratio is the p-value. This value is compared to a pre-determined α value that can identify varying sizes of statistical differences. A common α value is 0.05 relates to a 95% confidence interval, such that p-values less than 0.05 represent 95% confidence in statistically significant differences between at least two treatment effects (Dinov 2019).

When utilizing the ANOVA method, the remaining residuals need to meet three different criteria, known as Fisher conditions. These criteria are (1) the standard deviation of the residuals need to be relatively similar, where any deviations greater than two cause concern, (2) the residuals hug the normal density line closely with the box plot remaining symmetric, and (3) the mean of the residuals is zero (Cobb 2014). The greatest problem faced when meeting these criteria is that the pavement sections are reused for repeated measurements. Errors carried from year-to-year are not independent of each other. The statistical model used to evaluate the effectiveness of these preservation methods needs a way to address the variability from one pavement section to the next, beyond random variation experienced even within similar experimental units. Fortunately, the SP/RM experimental design and analysis can be tailored to do just that.

Split Plot/Repeated Measures Experimental Design

This section discusses the development of a SP/RM experimental design as applied to individual pavement preservation treatments. As this is a retrospective experiment, the discussion of the design, as well as an examination of its statistical appropriateness and limitations will be discussed.

An SP/RM experimental design relies on blocking of experimental units to reduce the amount of unexplained variance within a study. Blocking takes experimental units with similar properties and groups them accordingly in attempt to isolate the effect of different units (pavement sections) being treated the same. The experimental units in this study are the sections of pavement where the preservation treatments are applied, i.e. the project locations. The typical layout of an SP/RM experiment involves blocking of whole-plot and sub-plot factors, where both factors can be of varying size. The whole-plot factor in this situation will be whether the pavement receives a given preservation. The sub-plot factor will then be the index value measured according to their best-fit trends at relative year zero, one, or two.

Normally, an SP/RM design will split the experimental units into two blocks, based on the whole-plot factor. However, with each section of pavement having both post-preservation and estimated pre-preservation index values at relative years zero, one, and two, where relative years represent the time, in years, after the preservation treatment was applied, each pavement section is placed within a separate block, which then is subjected to both receiving and theoretically not receiving the preservation, via post-preservation and predicted pre-preservation trends, respectively. Table 4-1 visualizes this statistical design.

Table 4-1 *SP/RM experimental design setup*

Block	Pavement Section	Whole-Plot Factor: Pavement Preservation Applied	Sub-Plot Factor: 0 Years After Preservation Treatment	1 Years After Preservation Treatment	2 Years After Preservation Treatment
1	1	Yes	IV_{Post}	IV_{Post}	IV_{Post}
	1	No	IV_{Pre}	IV_{Pre}	IV_{Pre}
2	2	Yes	IV_{Post}	IV_{Post}	IV_{Post}
	2	No	IV_{Pre}	IV_{Pre}	IV_{Pre}
...	...	Yes	IV_{Post}	IV_{Post}	IV_{Post}
	...	No	IV_{Pre}	IV_{Pre}	IV_{Pre}
n	n	Yes	IV_{Post}	IV_{Post}	IV_{Post}
	n	No	IV_{Pre}	IV_{Pre}	IV_{Pre}

Note* IV_{Post} denotes index value from the post-treatment trend, IV_{Pre} – denotes index values from the pre-treatment trend

Typically, the ability for a statistical model to detect differences between varying factors relies on the number of replicates within the study. A study with 1000 experimental units would provide more accurate estimations of true means than a project with 10 experimental units. For example, the 23 microsurfacing projects analysis resulted in 138 total measurements, by means of 23 measurements for both application and no application of the preservation over the three sequential relative years. The strength of this study relies upon the quantity of observed projects for each flexible preservation method and is a drawback to this form of analysis.

The use of an SP/RM design typically requires two steps, including complete randomization and complete blocking. The complete randomization comes from the random assignment of whole-plot factors. The retrospective nature of this experiment does not allow for true randomization, as the pavement sections that received treatment versus those that didn’t cannot be randomly assigned. By treating the pre-treatment and post-treatment trends either a preserved or unpreserved pavement, each pavement section was constituent of its own block. So instead of complete randomization, a complete block design was utilized to better understand the actual differences between the preserved and unpreserved behavior of these pavement sections. The complete blocking of the subplot factor is achieved by repeated measurement of the same pavement sections at relative years zero, one, and two.

Table 4-2 *Partial analysis of variance table setup*

Source	DF	F-Ratio
Preservation	1	$\frac{MS_{Preservation}}{MS_{Preservation*Block}}$
Relative Year	2	$\frac{MS_{Relative\ Year}}{MS_{Error}}$
Preservation*Relative Year	2	$\frac{MS_{Preservation*Relative\ Year}}{MS_{Error}}$
Block&Random	(Qty. Pavement Sections)-1	$\frac{MS_{Block\&Random}}{MS_{Residual}}$
Preservation*Block&Random	(Qty. Pavement Sections)-1	$\frac{MS_{Preservation*Block\&Random}}{MS_{Residual}}$
Error	(C. Total DF)-(Sum DF Above)	-
Cumulative Total	(Qty. Pavement Sections*3)-1	-

Note* MS denotes mean square, DF denotes degrees of freedom

Table 4-2 breaks down the partial ANOVA structure for the statistical analysis. The whole-plot factor is represented by “Preservation”, and has one degree of freedom since there are only two options, yes or no. The F-Ratio for the preservation effect detects if there is a statistically significant difference in index values between pavements that received the preservation versus those that did not receive preservation and continued deteriorating. “Relative Year” has two degrees of freedom to represent the three measurements that were made, and its F-Ratio detects statistically significant differences in index values between each relative year. The interaction of the whole-plot and sub-plot treatment-levels is represented by crossing the factors, also seen on Table 4-2 as “Preservation*Relative Year”.

This F-Ratio can detect statistically significantly different index values across the six interactions of preservation and relative year: preservation (yes/no), relative year (0/1/2).

The last two unique sources of variance come from the blocks, and the interaction of the preservation effect and the blocks. The blocks are attributed with random error, seen as “&Random” within Table 4-2, under the assumption that these pavement sections are random amongst the total population of pavements needing preservation. This attribution is very important in these analyses as each pavement section is going to vary greatly from the others. This variation comes from factors, including but certainly not limited to, age, thickness, materials, condition, traffic level, climate, and speed limit. The inclusion of random error allows to model to disregard the variance of the different pavement sections to better isolate the effect of the preservation. This type of approach is done when the true means of each block are not necessary information. An example from Cobb (2014) discussed a study of three different IV fluid manufacturers. In a random effect setup, the actual means for each manufacturer are not necessary, under the assumption that these manufacturers represent the entire population of IV manufacturers, and the random effect comes from the selection of those three manufacturers (Cobb 2014). For this study, the random effect assigned to the pavement sections assumes the same conditions. The effect of each pavement section is not desired, but the overall effect of each preservation method, independent of pavement section is desired.

This SP/RM analysis was applied to the PCI, rutting, riding, and cracking indices for each of the four flexible pavement preservation methods, including microsurfacing, slurry sealing, patching, and crack sealing/filling.

Least Squares Mean Multiple Comparisons using Tukey's HSD

If any of the ANOVA analyses found statistically significant differences between the least squares means of the treatment effects, including the whole-plot factor, subplot factors, or their interaction effect, a Tukey's honest significant difference (HSD) test was performed to determine which treatments were different. This is an important process, as the ANOVA analysis will only share if a difference between at least two treatment effects' least square means with 95% confidence. Tukey's HSD can compare all the means to determine which treatments were different, and which treatments are statistically indifferent.

The HSD is a value determined by Equation 3 and if two different treatment effect's least squares mean difference is greater that the HSD, then the two treatments are statistically significantly different.

$$HSD = q_{A,\alpha}\sqrt{\frac{MS_{Error}}{Observations}} \tag{3}$$

Where $q_{A,\alpha}$ refers to q-value from the q-distribution based upon the model's varying degrees of freedom, MS_{Error} is the mean squared error of the model, and "Observations" is the total quantity of observations for each treatment effect interaction (Abdi and Williams 2010).

4.4 Results

From the trend fitting process that was applied to these projects, the PCI, rutting, riding, and cracking index values for both the post-treatment and predicted pre-treatment at zero, one, and two years after the preservation treatment were determined. The software utilized for the analysis was JMP Pro 14, and the data used within the JMP analyses was sourced from these tables.

4.4.1 Split Plot/Repeated Measures Analysis

This section presents the results from running the multiple SP/RM models for each pavement index across the four evaluated flexible pavement preservation treatments. Seen in Table 4-3 are the p-values from each model. By running the model with an α-level of 0.05, the resulting ANOVA p-values less than 0.05 represent a 95% confidence that at least two means of the factors of interest are statistically significantly different. Evaluation of these p-values is examined within this section.

Looking first at the microsurfacing pavement indices, the pavements that did receive preservation had statistically higher means for PCI, riding, and cracking indices. The rutting index was not found to have a statistically higher mean with preservation, indicating that these microsurfacings were likely placed to correct cracking and riding instead of ruts.

The slurry seal projects found no statistically different means between pavements that were preserved versus those that were not. Low index values at the time of preservation application were observed. With slurry seals shown to provide less benefit the further a pavement has deteriorated, these lower starting-quality pavements do not appear to have been ideal slurry sealing candidates (Hajj et al. 2011).

Hot mix asphalt patching provided similar detectable differences in preserved versus non-preserved pavement sections as microsurfacings did. The preserved pavements had higher means for the PCI, riding, and cracking indices, but no detectable difference was found for the rutting index. Since patching is a spot treatment, in combination with the low resolution of the PMS data, the rutting within the patched area is almost certainly very high in value, but it is not recognized within the entirety of the pavement section.

Table 4-3 *p-values for SP/RM index value analysis*

Microsurfacing		p-Values			
Sources of Variance	DF	PCI	Rutting	Riding	Cracking
Preservation	1	**<.0001**	0.7026	**<.0001**	**<.0001**
Relative Year	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Preservation*Relative Year	2	0.4405	0.6926	0.8336	0.9281
Block&Random	22	**<.0001**	0.1022	**<.0001**	**0.0016**
Preservation*Block&Random	22	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Error	88	α = 0.05, Confidence Intervals			
Cumulative Total	137	Determined With 95% Confidence			
Slurry Sealing		p-Values			
Sources of Variance	DF	PCI	Rutting	Riding	Cracking
Preservation	1	0.0103	0.969	0.0642	0.0982
Relative Year	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Preservation*Relative Year	2	0.2561	0.8113	**0.0455**	0.0873
Block&Random	12	**0.0007**	**0.043**	**<.0001**	0.0565
Preservation*Block&Random	12	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Error	48	α = 0.05, Confidence Intervals			
Cumulative Total	77	Determined With 95% Confidence			
Hot Mix Asphalt Patching		p-Values			
Sources of Variance	DF	PCI	Rutting	Riding	Cracking
Preservation	1	**0.0012**	0.9425	**0.008**	**0.0033**
Relative Year	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Preservation*Relative Year	2	0.4084	0.5025	0.8366	0.9938
Block&Random	28	**0.037**	**<.0001**	**0.001**	**<.0001**
Preservation*Block&Random	28	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Error	112	α = 0.05, Confidence Intervals			
Cumulative Total	173	Determined With 95% Confidence			
Crack Sealing/Filling		p-Values			
Sources of Variance	DF	PCI	Rutting	Riding	Cracking
Preservation	1	0.1539	**0.0004**	0.0897	0.524
Relative Year	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Preservation*Relative Year	2	0.0529	0.7073	0.9578	**0.003**
Block&Random	30	**<.0001**	**<.0001**	**<.0001**	**0.0347**
Preservation*Block&Random	30	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Error	120	α = 0.05, Confidence Intervals			
Cumulative Total	185	Determined With 95% Confidence			

Note* Bold-faces values represent a statistical difference between at least two of the factors of interest

The simplest preservation method, crack sealing/filling, has two primary goals of slowing the deterioration rate of growing cracks and preventing moisture infiltration within the pavement. Not surprisingly, the only detectable difference between preserved and non-preserved pavement was in the rutting index, where preserved pavements had a statistically greater mean.

Another section of Table 4-3 to note is that every single relative year p-value, regardless of preservation type or index, resulted in a statistically significant difference within at least two of the years. The interaction plots in the next section will show that every pavement index decreases from zero to one year after the preservation/maintenance treatment application, and one to two years after the preservation/maintenance treatment application, with at least a detectable difference from relative year zero to two.

4.4.2 Least Squares Means Interaction Plots

Since ANOVA is limited by only being able to tell is a difference exists, and not what the difference is, additional analysis of the interaction effect between relative year and preservation allows each treatment level effect to stand on its own. From the SP/RM analysis, a Tukey's honest significant difference (HSD) multiple comparison was made to determine any statistically different means across each relative year and application of the preservation treatment. Following Equation 3, the statistical output provides a value for Q, which stands in for the $q_{A,\alpha}$ value with 95% confidence, and mean squared difference, representing the square root of the mean squared error over total number of observations.

To simplify this comparison, JMP Pro 14 reports statistically similar means with a connected letters report. All means with a shared letter have a 95% confidence in statistical similarity, while means not sharing letters are significantly different. These results can be seen in Table 4-4, Table 4-5, Table 4-6, and Table 4-7. Visualization of the treatment effect interactions was performed by graphing the individual LS means in conjunction with the HSD intervals used to evaluate statistical differences.

Table 4-4 *Microsurfacing HSD comparisons*

Application	Index	Preservation/ Year	Least Squares Mean	Q	Standard Error Difference	HSD	Connected Letters Report			
Microsurfacing	PCI	Yes,0	74.0	2.91	0.43	1.27	A			
		Yes,1	73.0	2.91	0.43	1.27	A	B		
		Yes,2	72.1	2.91	0.43	1.27		B		
		No,0	60.8	2.91	0.43	1.27			C	
		No,1	59.9	2.91	0.43	1.27			C	
		No,2	58.3	2.91	0.43	1.27				D
	Rutting	No,0	54.9	2.91	0.50	1.46	A			
		No,1	54.1	2.91	0.50	1.46	A	B		
		Yes,0	53.4	2.91	0.50	1.46		B	C	
		No,2	52.9	2.91	0.50	1.46		B	C	
		Yes,1	52.3	2.91	0.50	1.46			C	
		Yes,2	50.7	2.91	0.50	1.46				D
	Riding	Yes,0	73.1	2.91	0.36	1.04	A			
		Yes,1	72.3	2.91	0.36	1.04	A	B		
		Yes,2	71.5	2.91	0.36	1.04		B		
		No,0	61.4	2.91	0.36	1.04			C	
		No,1	61.0	2.91	0.36	1.04			C	D
		No,2	60.1	2.91	0.36	1.04				D
	Cracking	Yes,0	82.2	2.91	0.70	2.05	A			
		Yes,1	80.8	2.91	0.70	2.05	A	B		
		Yes,2	78.9	2.91	0.70	2.05		B		
		No,0	61.2	2.91	0.70	2.05			C	
		No,1	60.2	2.91	0.70	2.05			C	D
		No,2	58.2	2.91	0.70	2.05				D

Note* Connected letters represent statistical similarly between means with a 95% confidence level

Table 4-5 *Slurry sealing HSD comparisons*

Application	Index	Preservation/ Year	Least Squares Mean	Q	Standard Error Difference	HSD	Connected Letters Report				
Slurry Seal	PCI	Yes,0	64.5	2.96	0.68	2.02	A				
		Yes,1	61.8	2.96	0.68	2.02		B			
		Yes,2	60.1	2.96	0.68	2.02		B			
		No,0	56.4	2.96	0.68	2.02			C		
		No,1	54.6	2.96	0.68	2.02			C		
		No,2	51.2	2.96	0.68	2.02				D	
	Rutting	No,0	60.0	2.96	0.87	2.60	A				
		Yes,0	59.7	2.96	0.87	2.60	A				
		No,1	58.8	2.96	0.87	2.60	A	B			
		Yes,1	58.4	2.96	0.87	2.60	A	B			
		Yes,2	57.0	2.96	0.87	2.60		B			
		No,2	56.7	2.96	0.87	2.60		B			
	Riding	Yes,0	55.7	2.96	0.36	1.06	A				
		Yes,1	55.2	2.96	0.36	1.06	A	B			
		Yes,2	54.2	2.96	0.36	1.06		B			
		No,0	53.0	2.96	0.36	1.06			C		
		No,1	51.9	2.96	0.36	1.06				D	
		No,2	50.1	2.96	0.36	1.06					E
	Cracking	Yes,0	68.2	2.96	1.07	3.19	A				
		Yes,1	66.8	2.96	1.07	3.19	A	B			
		Yes,2	64.8	2.96	1.07	3.19		B			
		No,0	57.2	2.96	1.07	3.19			C		
		No,1	54.6	2.96	1.07	3.19			C		
		No,2	50.4	2.96	1.07	3.19				D	

Note* Connected letters represent statistical similarly between means with a 95% confidence level

Table 4-6 *HMA patching HSD comparisons*

Application	Index	Preservation/ Year	Least Squares Mean	Q	Standard Error Difference	HSD	Connected Letters Report					
HMA Patching	PCI	Yes,0	60.5	2.89	0.45	1.31	A					
		Yes,1	58.6	2.89	0.45	1.31		B				
		Yes,2	56.6	2.89	0.45	1.31			C			
		No,0	50.2	2.89	0.45	1.31				D		
		No,1	48.8	2.89	0.45	1.31					E	
		No,2	45.9	2.89	0.45	1.31						F
	Rutting	Yes,0	47.7	2.89	0.58	1.70	A					
		No,0	47.0	2.89	0.58	1.70	A					
		Yes,1	46.4	2.89	0.58	1.70	A	B				
		No,1	46.2	2.89	0.58	1.70	A	B				
		No,2	45.2	2.89	0.58	1.70		B				
		Yes,2	44.9	2.89	0.58	1.70		B				
	Riding	Yes,0	48.7	2.89	0.60	1.75	A					
		Yes,1	47.2	2.89	0.60	1.75	A					
		Yes,2	44.7	2.89	0.60	1.75		B				
		No,0	40.0	2.89	0.60	1.75			C			
		No,1	38.7	2.89	0.60	1.75			C			
		No,2	36.4	2.89	0.60	1.75				D		
	Cracking	Yes,0	72.9	2.89	0.77	2.24	A					
		Yes,1	71.5	2.89	0.77	2.24	A					
		Yes,2	69.0	2.89	0.77	2.24		B				
		No,0	61.5	2.89	0.77	2.24			C			
		No,1	60.0	2.89	0.77	2.24			C			
		No,2	57.5	2.89	0.77	2.24				D		

Note* Connected letters represent statistical similarly between means with a 95% confidence level

Table 4-7 *Crack Sealing/Filling HSD comparisons*

Application	Index	Preservation/ Year	Least Squares Mean	Q	Standard Error Difference	HSD	Connected Letters Report				
Crack Sealing/Filling	PCI	Yes,0	65.5	2.89	0.38	1.10	A				
		Yes,1	64.1	2.89	0.38	1.10		B			
		No,0	62.6	2.89	0.38	1.10			C		
		Yes,2	62.1	2.89	0.38	1.10			C		
		No,1	61.8	2.89	0.38	1.10			C		
		No,2	60.5	2.89	0.38	1.10				D	
	Rutting	Yes,0	61.6	2.89	0.52	1.53	A				
		Yes,1	60.1	2.89	0.52	1.53	A				
		Yes,2	58.2	2.89	0.52	1.53		B			
		No,0	50.8	2.89	0.52	1.53			C		
		No,1	49.6	2.89	0.52	1.53			C		
		No,2	48.0	2.89	0.52	1.53				D	
	Riding	Yes,0	55.7	2.89	0.30	0.88	A				
		Yes,1	54.7	2.89	0.30	0.88		B			
		No,0	54.3	2.89	0.30	0.88		B	C		
		Yes,2	53.6	2.89	0.30	0.88			C	D	
		No,1	53.3	2.89	0.30	0.88				D	
		No,2	52.1	2.89	0.30	0.88					E
	Cracking	Yes,0	78.2	2.89	0.70	2.03	A				
		Yes,1	76.1	2.89	0.70	2.03		B			
		No,0	74.4	2.89	0.70	2.03		B	C		
		No,1	73.3	2.89	0.70	2.03			C	D	
		Yes,2	71.9	2.89	0.70	2.03				D	
		No,2	71.5	2.89	0.70	2.03				D	

Note* Connected letters represent statistical similarly between means with a 95% confidence level

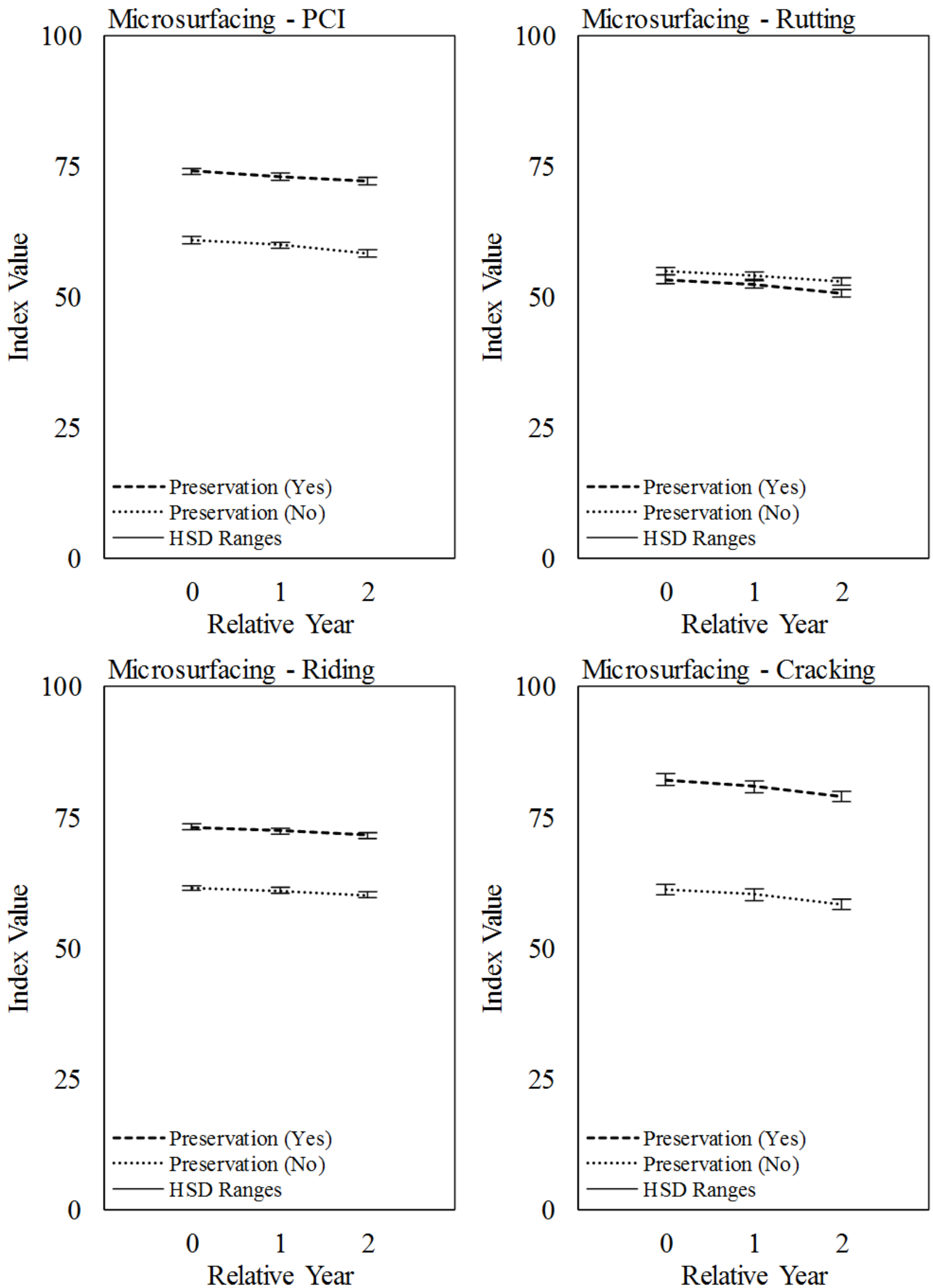

Figure 4-1 *Microsurfacing LS means interaction plots with 95% confidence intervals*

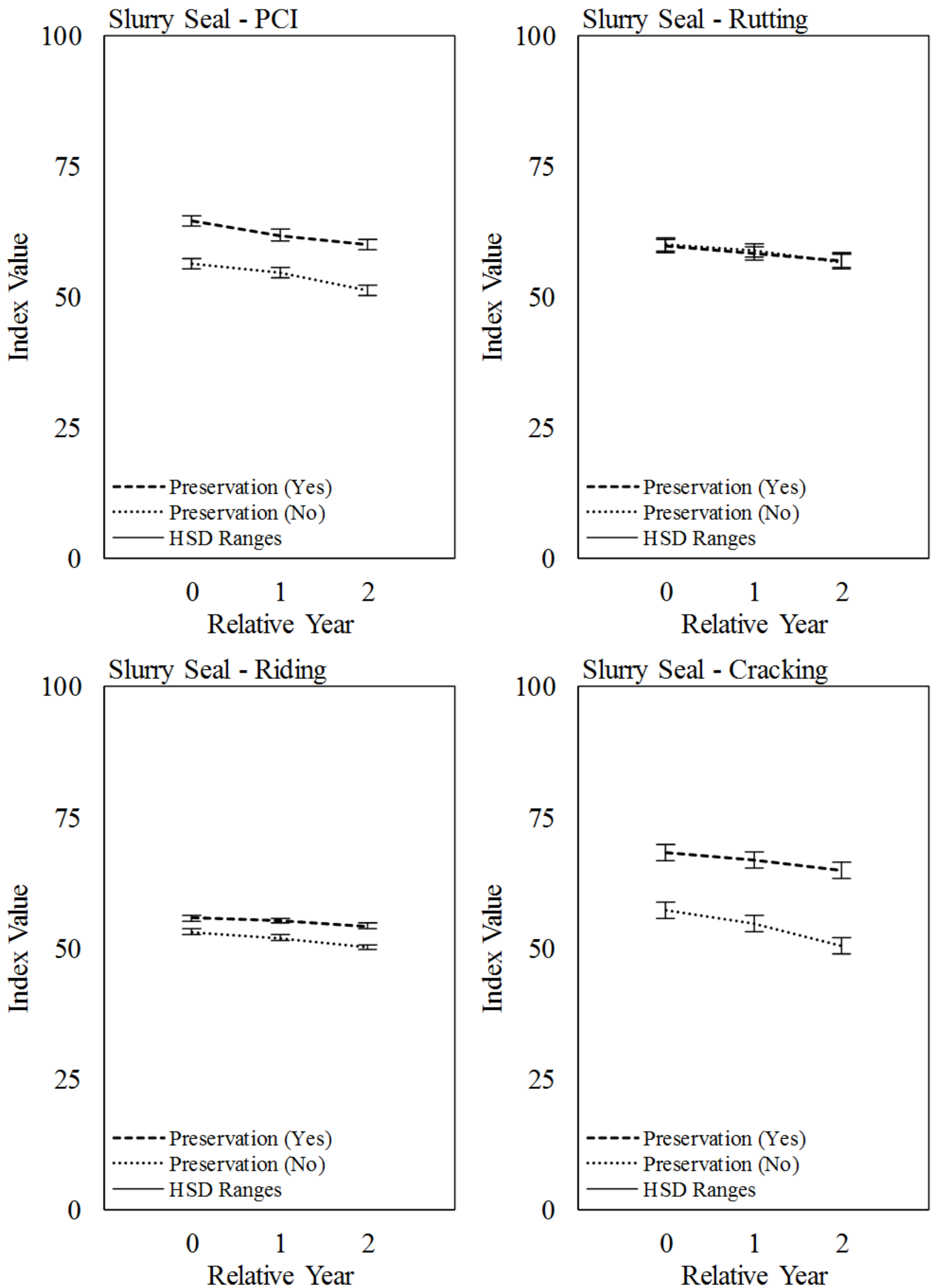

Figure 4-2 *Slurry seal LS means interaction plots with 95% confidence intervals*

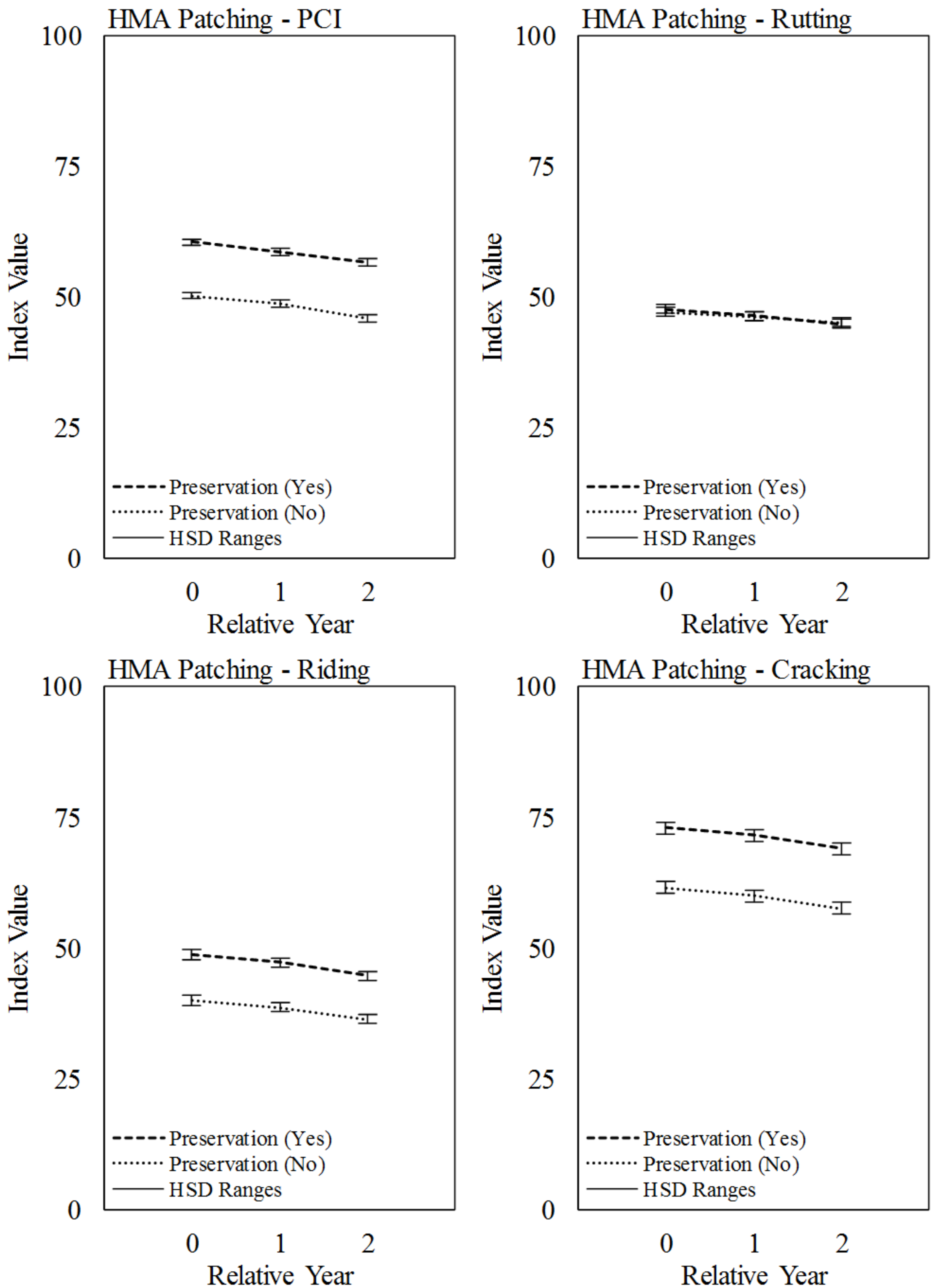

Figure 4-3 *HMA patching LS means interaction plots with 95% confidence intervals*

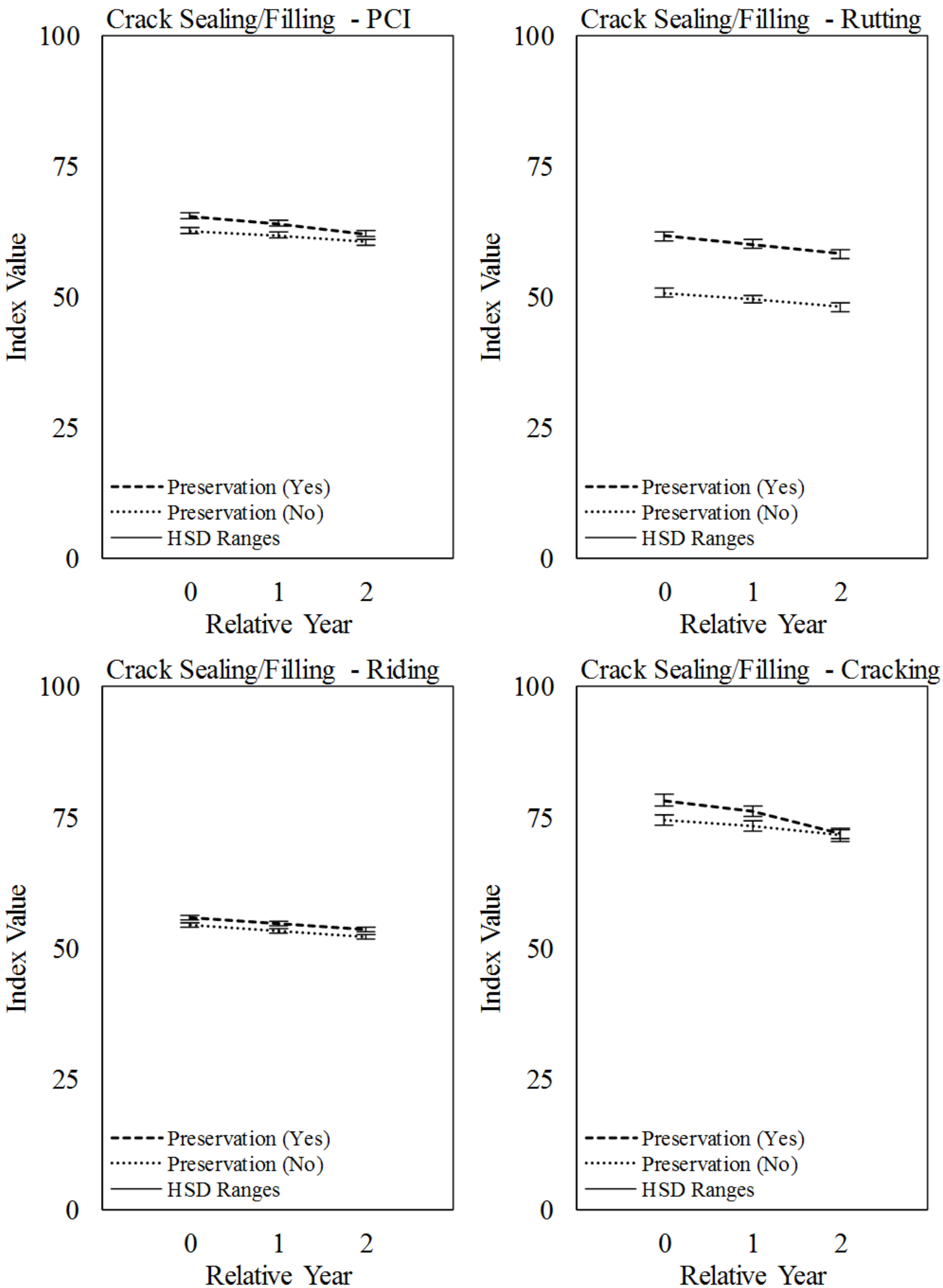

Figure 4-4 *Crack sealing/filling LS means interaction plots with 95% confidence intervals*

The four pavement indices for microsurfacings, seen in Figure 4-1, confirm the ANOVA results with statistically significantly higher means for preserved compared to unpreserved pavements for PCI, riding, and cracking indices, providing average index value improvements of 13, 11, and 20, respectively. For the rutting index, only a two-point difference in value was found between preserved and unpreserved pavement sections, indicating virtually no difference between the whole-plot factor (preservation/no preservation). Table 4-4 shows the connected letters report for the interaction effect, confirming that the HSD found differences between preservation and no preservation at each relative year, but substantial overlap was seen year-to-year between the two.

Slurry sealing provided similar results to the microsurfacings when comparing the treatment effect interactions as well, seen in Figure 4-2. Average improvements of 8, 3, and 12 points for the PCI, riding, and cracking index were observed. The rutting index values were almost identical between preserved and unpreserved pavements, with no year larger than 0.5 points different. The connected letters report in Table 4-5, shows the only statistical differences were the year the treatment was applied and two years after treatment for both preserved and unpreserved pavement sections, signaling the perpetual deterioration of the index across time.

When comparing the treatment effect interactions for HMA patching in Figure 4-3, the rutting index was nearly identical at each relative year as well. While still statistically similar, the largest observed difference was just over 0.5 index points the year the HMA patching maintenance was applied, and the connected letters report in Table 4-6 shows preserved/unpreserved year zero and one values to all share statistically similar means. The preserved/unpreserved year 2 values overlapped with the preserved/unpreserved year 1 values but were not like year 0 values. This result was identical to that seen for slurry sealing. Average improvements from preservation for the PCI, riding, and cracking index were 10, 8, and 11 points, respectively.

Figure 4-4 and Table 4-7 display the results from comparing means for the crack sealing/filling projects, and the behavior was unlike the previous three types of preservation methods. PCI saw an average index improvement of 2 points, with the value of preserved pavement sections at relative year two falling back to the unpreserved values at relative years one and two. The rutting index saw highly significant improvement from preservation, with an average improvement of 10 points. The riding index, in this case, performed similar to the rutting index of the other preservation methods. Both preserved and unpreserved pavements were within two points for each relative year, and both trends ended significantly lower than their starting values. Interestingly, the cracking index was improved by almost four points the year the preservation treatment was applied, but by two years after application, both trends had statistically indifferent index values.

4.5 Conclusions

The SP/RM resulted in multiple p-values that signaled at least two treatment effects were statistically significantly different, at a confidence interval of 95%. This analysis was helpful for the whole-plot factor of preserved and unpreserved pavements. It was found that microsurfacing and patching both resulted in higher PCI, riding, and cracking index values. Crack sealing/filling was the only preservation that resulted in statistically significantly higher rutting index values.

The next step in the analysis was to compare the average means of each interaction effect between the whole-plot and subplot factors. Using Tukey's HSD statistical approach, 95% confidence was achieved in detecting like, and unlike, interaction effects. Ultimately, this step evaluated the effect of each preservation, while assigning additional variation to each relative year, to detect smaller differences.

Microsurfacing, slurry sealing, and patching all showed statistically higher index values for their PCI, riding, and cracking indices at all three analyzed relative years. Of these three preservation methods, microsurfacings improved all three indices the most. The PCI, riding, and cracking indices saw a 13-point, 11-point, and 20-point improvement on average, respectively. All three of these preservation methods, however, detected no statistically significant difference at any relative year for the rutting index. The only flexible preservation to do so was crack sealing/filling, with an average improvement of 10 points.

As microsurfacings are typically used to address rutting, it is likely that these applications were primarily in response to cracking and riding related distresses, or the pavement sections have structural or material deficiencies. The slurry sealing is a very thin application and was not expected to improve rutting, and HMA patches likely addressed the local rutting, but were restricted in global improvement by their small footprint.

The other important takeaway from the interaction plots was the surprisingly parallel trends for preserved and unpreserved pavements. The only two instances in which a greater than two-point difference in preserved index value minus unpreserved index value across all three years was the slurry sealing and crack sealing/filling cracking indices. This shows that index improvements for preserved and unpreserved pavements are independent of relative year. In addition, every single index for all four preservation types had statistically lower relative year two values compared to relative year zero values for both preserved an unpreserved pavements, indicating significant deterioration within two years of application.

4.6 Discussion

Depending on case-by-case need, the implementation of an SP/RM experimental design can provide historical insight to the realistic expectations of pavement performance. By utilizing the model to account for wide variation between pavement sections, the ability to see a treatment by time interaction interjects another level of confidence in comparative analysis. Careful analysis of these sensitive data sets show the process to be extensive, but necessary for accurate pavement preservation performance behavior.

4.6 References

Adbi, H., Williams, L., 2010. Tukey's Honestly Significant Difference (HSD) Test. *Encyclopedia of Research Design*, Thousand Oaks, California: Sage.

Bektas, F., et. al., 2014. *Pavement Management Performance Modeling: Evaluating the Existing PCI Equations.* INTRANS Project 13-455, Iowa DOT Project SPR RB14-013.

Buss, A., et. al., 2018. Extracting More from Dynamic Modulus Data Using Split-Plot Repeated Measures Analysis. *ASTM Journal of Testing and Evaluation*, 46(1), 351–364.

Cobb, G. W., 2014. The Principle of Blocking. *Introduction to Design and Analysis of Experiments*, Daryaganj, New Delhi: Wiley, 243-309.

Dinov, I. D., 2019. *Statistics Online Computational Resource: F Distribution Tables* [online]. University of California Los Angeles Department of Statistics. Available from: http://www.socr.ucla.edu/Applets.dir/F_Table.html [Accessed 22 Apr 2019].

Dong, Q., Huang, B. H., 2012. Evaluation of Effectiveness and Cost-Effectiveness of Asphalt Pavement Rehabilitations Utilizing LTPP Data. *ASCE Journal of Transportation Engineering*, 138(6).

Dwight-Hixon, C., and Ooten, D. A., 1993. Nine years of microsurfacing in Oklahoma. *Transportation Research Record*, 1392, 13–19.

FHWA, 2014. *Distress Identification Manual for the Long-Term Pavement Performance Program*. Publication No. FHWA-HRT-13-092.

Galehouse, L., et. al., 2003. Principles of Pavement Preservation Definitions, Benefits, Issues, and Barriers. *Transportation Research Record*, 228.

Hajj, E. Y., et. al., 2011. Optimum Time for Application of Slurry Seal to Asphalt Concrete Pavements. *Transportation Research Record*, 2235, 66-81.

Iowa DOT., 2017. *Iowa DOT Open Data* [online]. Iowa Department of Transportation. Available from: http://data.iowadot.gov/datasets/48bfff7ffbfa4555bed8c374e44c9300_1 [Accessed 01 May 2018].

ISSA, 2010. *High Performance Slurry Systems Inspector's Manual*. Annapolis, MD: International Slurry Surfacing Association.

Johnson, D., et. al., 2000. Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements. *Transportation Research Record*, 1697, 31-40.

Park, K., et. al., 2007. Applicability of the International Roughness Index as a Predictor of Asphalt Pavement Condition. *ASCE Journal of Transportation Engineering*, 133(12), 706-709.

NCHRP, 2014. *Pavement Patching Practices*. National Cooperative Highway Research Program, Synthesis 463. Transportation Research Board. Washington, D.C.

CHAPTER 5. LIFE CYCLE COST ANALYSIS FOR FLEXIBLE PAVEMENT PRESERVATION METHODS

Modified from the paper titled "Life-Cycle Cost Analysis Based on State-Sourced Flexible Pavement Preservation Performance Data," currently under peer-review for the International Journal of Pavement Engineering.

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5.1 Abstract

By extracting relevant performance indicators from the Iowa Department of Transportation's (DOT) pavement management system (PMS), the effectiveness of four types of flexible pavement preservation methods, including microsurfacing, slurry sealing, patching, and crack/joint sealing, was determined. Companied by recent average cost data for similar projects managed by the Iowa DOT, the expected preservation performance allows for a life cycle cost analysis (LCCA) to compare these different treatments by costs, as well as performance. A LCCA used collected pavement performance information for treatment deterioration curves, and fit current and discounted future values of construction, maintenance, and salvage values to provide a means of comparing varying alternatives for cost-effectiveness by their respective net present values (NPVs) or other similar parameters, such as equivalent uniform annual cost and cost/index benefit. The resulting equivalent annual uniform cost (EAUC) values showed the costliest of the four preservation methods was patching, followed by microsurfacing, slurry sealing, and crack/joint sealing, in that order. Cost effectiveness related to the quantity of index improvement yielded slurry sealing,

at a cost of $192 (USD) per pavement condition index (PCI) improvement, to be the cheapest preservation method at improving the overall pavement quality. Common variables of high sensitivity within a LCCA are the discount rate and the length of the analysis period. A sensitivity analysis of the discount rate showed the microsurfacing projects to display the largest impact as a result of their longer index service life extensions, compared to the other preservation methods, while an additional sensitivity analysis on the length of the LCCA analysis periods showed extreme variations between the 5- and 10-year analysis period lengths. The cost per index benefit showed a 30% difference, on average, between the 5- and 10-year analyses, when compared to the original LCCA results. The standard LCCA method was adapted to accommodate less substantial flexible pavement preservation methods.

5.2Introduction

An increasingly common tool used by agencies for pavement infrastructure is the life-cycle cost analysis (LCCA) method. To perform a LCCA for flexible pavement preservations, three essential categories are needed, including expected performance, historical cost data, and time-related data. By extracting relevant performance indicators from the Iowa Department of Transportation's (DOT) pavement management system (PMS), the behavior of four different flexible pavement preservation methods, including microsurfacing, slurry sealing, patching, and crack/joint sealing, was determined. Companied by recent average cost data for similar projects let by the Iowa DOT and relevant discount rates, the expected preservation performance allows for a life cycle cost analysis to compare these different treatments by costs, as well as performance. The economic analysis incorporated current costs and used constant dollars to discount future values of construction, maintenance, and salvage values of four different pavement performance-based indices. Comparison of these indices across each preservation method provided a means of comparing varying alternatives for cost-effectiveness by their respective equivalent uniform annual cost (EUAC) and cost/index benefit, both of which are based off the net present value (NPV), the primary output of a LCCA (Walls et al. 1998).

5.2.1 Flexible Pavement Preservation Methods

Flexible pavement preservation methods consist of any construction activity that attempts to alleviate distress of an asphalt-based pavement or pavement surface. These distresses are caused by deterioration of pavement material properties, stresses on the pavement structure, and temperature and moisture conditions (Tseng et al. 1989). Over time, many different preservation approaches have been tried, but common methods include microsurfacing, slurry sealing, chip sealing, patching, crack sealing, and joint sealing; these treatments are expected to extended pavement service lives anywhere from one to seven years (Galehouse 2002). Microsurfaced pavements, slurry seals, and chip seals fall are methods that treat large areas of flexible pavement roadways typically applied on fair- or good-condition pavements, while patching and crack/joint sealing are more often utilized as spot treatments. Patching primarily addresses area of more severe pavement distresses, and crack/joint sealing addresses all present cracking.

5.3 Materials and Methods

5.3.1 Materials

This study involved the continued analysis on a variety of flexible pavement preservation projects. 103 total projects were evaluated, where 23 of the projects were microsurfacing, 13 were slurry seals, 34 were hot mix asphalt (HMA) patching, and 33 were HMA joint and crack sealing. The selection of these projects was provided via an Iowa DOT supplied list. This list included projects that had collected data within the Iowa DOT's 1998 to 2017 PMS database with the preservation activity occurring no later than 2016, such that at least two years of post-preservation data had been collected.

The second source of data that was collected came from the Iowa DOT's historical bid tabulations. All construction documents for Iowa DOT managed projects since January of 2014 are made publicly accessible, and for any given project, all received bids are ranked from first to last by bid total. The tabulations then break down each construction item by quantity and cost. By analyzing all bid-items and project quantities, a six-year average cost for each relevant line-item was determined.

5.3.2 Methods

Historical Cost Data

To obtain accurate estimations of cost data for these flexible pavement preservation methods, historical bid tabulations from the Iowa DOT were examined. The Iowa DOT bid tabulations are publicly accessible for projects dating from present to the beginning of 2014, at the time of this study (Iowa DOT 2019b). After collecting all available tabulations, the analysis yielded cost data for specific line items associated with the direct costs for each preservation method.

When collecting cost data for each project type, certain line items were ignored due to the indirect relation to the cost of each preservation. For example, mobilization costs, flagging costs, and even pilot car operation costs were typically involved with the overall cost of the project, but just because one contractor charged twice as much for mobilizing their equipment does not mean those costs had to be associated with the method of preservation. Table 5-1 shows the bid-line items collected for each preservation type.

Table 5-1 *Iowa DOT Bid Tabulation Line Items*

Preservation	Bid-Line Item	Priced by Unit
Microsurfacing	Preparation of Surface for Microsurfacing	Mile
	Emulsified Asphalt for Microsurfacing	Gallon
	Aggregate for Microsurfacing	Ton
	Painted Pavement Marking	Station (Mile)
Slurry Seal	Surface Preparation for Strip Slurry Treatment	Mile
	Asphalt Emulsion for Slurry Treatment	Gallon
	Strip Slurry Treatment Aggregate	Ton
	Slurry Levelling	Mile
	Painted Pavement Parking	Station (Mile)
Patching	Hot Mix Asphalt (Partial Depth)	Ton
	Regular Partial Depth Hot Mix Asphalt Finishing	Square Yard
	Painted Pavement Parking (If Needed)	Station (Mile)
Crack/Joint Sealing	Crack and Joint Cleaning and Sealing	Mile
	Sealer Material (HMA Surfaces)	Pound
	Painted Pavement Parking (If Needed)	Station (Mile)

After collecting data from a wide number of historic projects, the bid-line items were related back to a cost-per-mile basis. The microsurfacing, slurry sealing, and crack/joint sealing projects took each line item's cost, divided by the overall project length. This was done regardless of the line items being material costs or labor-based costs. Unlike the other three preservation methods, the patching projects were first related to a patch density by taking the total square yards of surface finished patches and dividing it by the projects area, resulting in a percentage of a square yards of patching per two lane-miles. The traffic lanes were 12 feet each, and the patch density assumed two lanes, as the historical patching projects were seen to patch both sides of a road during the same project.

Table 5-2 shows the results of the historical cost data collection, broken out according to preservation type. It was seen that the from these six years of data, microsurfacing and patching projects are the most expensive, with slurry sealing and crack/joint sealing at about 65% and 85% less expensive, respectively. The LCCA's performed within this study examined the correlation between the original construction costs and the overall performance benefits to determine if allocation of additional funds upfront would result in an increased cost-effectiveness overall.

Table 5-2 *Average costs per lane mile*

Preservation	Cost Itemization		Cost/Lane-mile
Microsurfacing (58 averaged projects)	Surface Preparation		$2,435.97
	Emulsion		$9,390.63
	Aggregate		$6,479.01
	Paint		$1,204.45
		Total	**$19,510.06**
Slurry Seal (28 averaged projects)	Surface Preparation		$968.25
	Slurry Levelling		$2,248.10
	Emulsion		$1,811.01
	Aggregate		$1,223.15
	Paint		$590.68
		Total	**$6,841.19**
Patching (20 averaged projects)	Average % of Surface/2 Lane-mile)		2.45%
	Patching Material		$11,469.48
	Patch Finishing		$7,382.01
	Paint		$547.39
		Total	**$19,398.87**
Crack/Joint Sealing (147 averaged projects)	Sealing		$1,717.07
	Sealant		$1,268.64
		Total	**$2,985.72**
Annual Maintenance	On 5-Year Growth Sliding Scale		**$2,500**

Pavement Condition Indices and Performance Modelling

The Iowa DOT's PMS contained a wide variety of pavement related information for all the primary roadways within the state (Iowa DOT 2019a). Collected by a third-party, the information for each unique identifier of varying lengths of the pavements, designated as original smart keys, are is input into the PMS every year since 1998. These original smart keys each contain pavements sections with identical pavement structure, and all relevant data since 1998 was collected for each of the evaluated projects. Some projects have singular original smart keys, while others can have multiple. By relating the year that each preservation was performed to a relative year zero, all the preservation projects were then set on comparable timelines. The years before the preservation took on negative values, and the years after took on positive values, such that if a preservation was applied in 2005, the years 2004 and 2006 would be relative years negative one and one, respectively.

To determine the effect of each preservation type, four different pavement indices were examined. These indices were the pavement condition index (PCI), rutting index, riding index, and cracking index. All four indices are on a scale of zero to 100, with the latter three remaining unique to the Iowa DOT. A value of 100 represents excellent performance, while zero represents a completely failing criteria. PCI provides an overall indication of the current state for a pavement's condition. The equation for PCI, currently used by the Iowa DOT, comes from a recent InTrans study (2014) that related index rating to the existing PCI values (Bektas et al. 2014). This relationship can be seen in Equation 1, where the coefficients of each index determine the weighting of cracking, riding and rutting indices into the value of PCI.

$$PCI = 0.4 \times (Cracking\ Ind.) + (0.4 \times\ Riding\ Ind.) + (0.2 \times Rutting\ Ind.) \quad (1)$$

The rutting index evaluates average rut depths of 12 mm or greater as a zero, and no rutting as a value of 100. The riding index evaluates collected International Roughness Index (IRI) values greater than 4 m/km as a zero, and IRI values less than 0.5 m/km are represented as 100 on the index. The cracking index relates four different individual cracking distress indices into one conglomerate value to represent the overall condition of cracks. No cracking is evaluated as a 100, while severe cracking can lead to an index value of zero.

From this approach, the next step was determining all relevant yearly data to best-fit performance trend lines. Any significant jumps in the index values before relative year zero were indicative of interaction with the pavement, through either another preservation method, rehabilitation, or reconstruction. Similarly, a jump in index value after relative year zero represented post-preservation activity. The values before the last pre-preservation and after the first post-preservation activities were ignored during the fitting of the pre- and post-preservation best-fit functions. The use of either linear, second-order polynomial, or reflected logistic sigmoidal functions was evaluated according to which function provided the least summation of the squared error in accordance with the Original Smart Key data. All three functions were restricted to maximum and minimum values of 100 and zero, as well as a zero or negative slope, to best represent the typical maintenance or deterioration of a pavement's performance, respectively.

Index Value Benefits, Service Life Extensions, and Threshold Values

With both trend lines determined, the initial index value benefit was determined by subtracting the pre-preservation index value from the post-preservation index value at relative year zero. This provided the improvement, if observed, for each pavement index because of the preservation activity.

The service life extensions for each index were determined by first finding the index value of the pre-preservation trend line at relative year zero, and then solving the post-preservation deterioration curve function using the pre-preservation index value at relative year zero. To obtain the length of time it takes for the pavement index to deteriorate back to the initial index value at the time of the preservation. For example, if a preservation method improved a pavement's index value by 10, and had a linearly decreasing post-preservation trend of 1 point per relative year, then the service life extension would obtain a value of 10 years.

The use of the pre-preservation index value at relative year zero, needed to determine the value at which the service life extension is over, effectively turns these pre-preservation values into the threshold values. Threshold values are utilized in a LCCA to determine the timing at which a construction activity will be performed. This study examined fixed threshold values, as determined from the performance modelling, but variable preservation timing could result in an optimized schedule of pavement preservations.

Table 5-3 *Average LCCA input values*

Preservation	Pavement Index	Service Life Extension	Threshold Value	Index Value Benefit
Microsurfacing (23 averaged projects)	PCI	3.7	60.8	13.2
	Rutting	2.4	55.0	**-1.6***
	Riding	3.3	61.5	11.6
	Cracking	5.3	61.2	21.0
Slurry Seal (13 averaged projects)	PCI	3.0	56.4	8.2
	Rutting	2.2	60	4.5
	Riding	2.6	53.1	3.5
	Cracking	3.0	57.2	14.4
Patching (34 averaged projects)	PCI	3.4	50.3	9.9
	Rutting	2.1	59.5	4.2
	Riding	2.6	39.1	8.3
	Cracking	3.5	61.5	12.5
Crack/Joint Sealing (33 averaged projects)	PCI	2.2	61.7	4.2
	Rutting	2.9	57.5	12
	Riding	1.6	52.6	2.2
	Cracking	2.3	74.2	8.3

Note: * Denotes instance where the index has worsened after the preservation was applied

Table 5-3 displays the average index value benefits, average service life extensions, and average threshold values that were determined for each of the flexible pavement preservation methods prior to running a LCCA. The only instance where a pavement observed worse index performance after the preservation was applied was the rutting index of microsurfacing projects. Due to this abnormality, this instance was not calculated throughout the remainder of this study.

Life-Cycle Cost Analysis

To run a fixed LCCA, four unique input values are required. These inputs are the cost of the preservation, the initial index value benefit, the index service life extension, and the index threshold values, which are already laid out in Table 5-2 and Table 5-3. In addition to these inputs, certain analysis parameters are also decided at this point. Arguably the most important parameter is the discount rate used to determine the net present value of the preservation costs, maintenance costs, and salvaged service life value. According to the OMB Circular from the Executive Office of the President, the current real discount rates on treasury notes and bonds for 2018 is 1.3% for 3, 5, and 7-year analyses, 1.4% for 10-year analyses, and 1.5% for both 20- and 30-year analysis (Mulvaney 2018). These rates are recommended for use when performing cost-effective related analysis for constant dollar flows.

The difference between a fixed and probabilistic LCCA is how these input parameters are included in the analysis. Fox fixed LCCA, discrete singular values are determined to best represent the desired conditions, while a probabilistic LCCA uses individual probability models for each input parameter. The returned output then accounts for the collective probabilities for each parameter (Walls et al. 1998). A probabilistic approach can be a very powerful analytical method, but the small set of available data renders this approach to be highly assumptive.

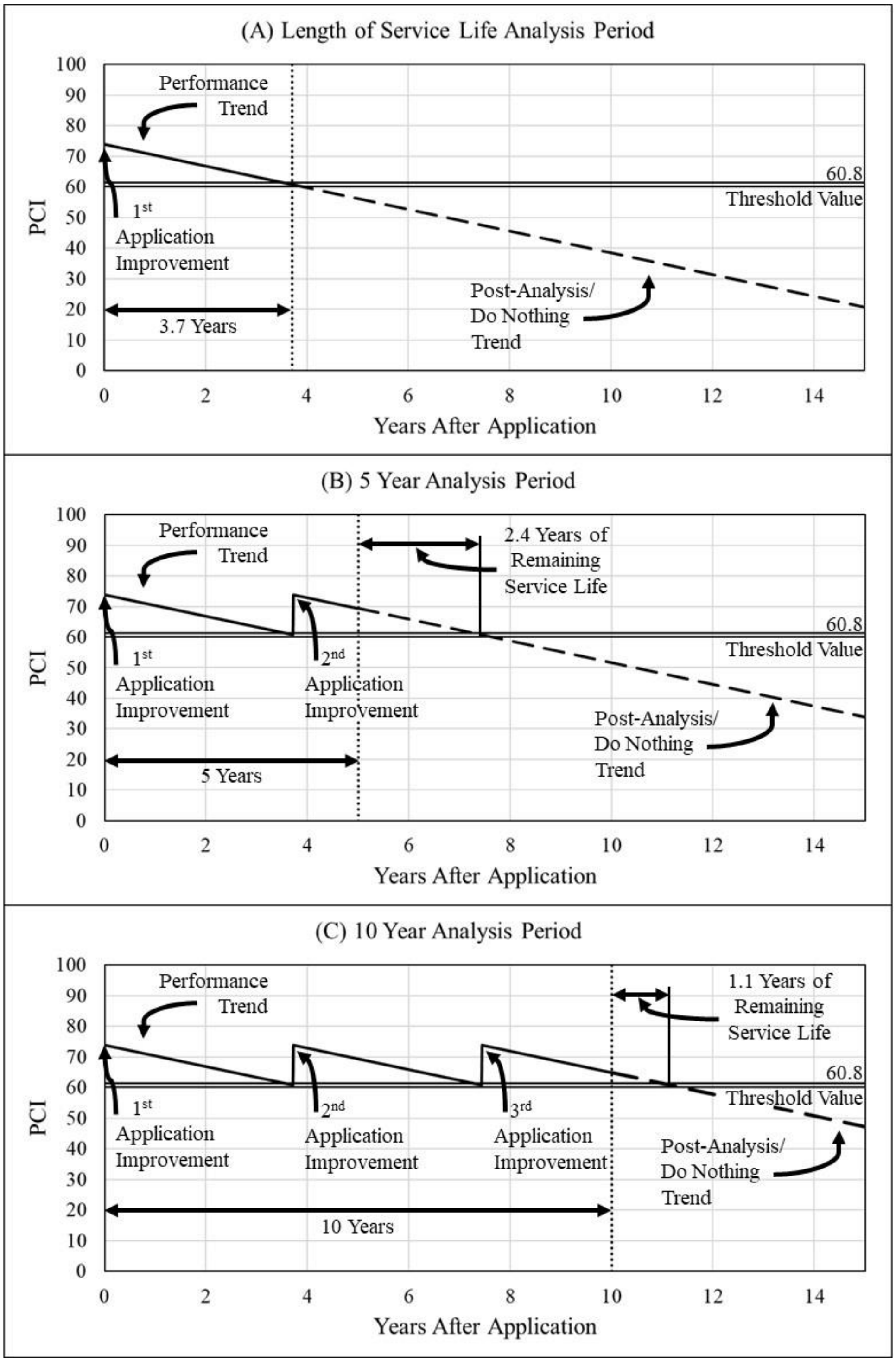


Figure 5-1 *Graphical example of LCCA with analysis periods of lengths equal to (A) service life, (B) 5-years, and (C) 10-years*

With these inputs all prepared, the general breakdown of this LCCA was performed as follows: (1) The preservation methods are applied first at relative year zero and provide an index value equal to the threshold value plus said index value benefit, (2) the performance of the index is assumed to be linear from this starting value over the duration of the calculated index service life, at which the index value has fallen to its threshold value, (3) the analysis period was evaluated at the length of each index service life extension, five years, and ten years, (4) for the five- and ten-year analyses, when the index value hit the threshold value, the same preservation was re-applied, and provided similar performance, and (5) any remaining service life after the analysis period was salvaged as a deduction in overall net present value. A graphical explanation of this LCCA can be seen in Figure 5-1.

The assumption of linear performance trends was made to account for the wide variability within the small set of flexible pavement preservation projects evaluated by best fit trendlines. Additional projects would increase the confidence of the performance trends, but linearly deteriorating pavements for this LCCA simplifies the analysis and is better for accommodating shorter service life extensions. When compared to rehabilitation and reconstruction projects, the shorter service lives render small deviations from linearity to have trivial impact on the final result.

Any time the preservation was applied multiple times, as per the 5- and 10-year analyses, the present value needed to be determined. Equation 1 displays the method used to relate these future values to a present dollar amount (Walls et al. 1998).

$$PV = \frac{Initial\ Cost \times (1+i)^n}{(1+i)^n} \tag{1}$$

Where PV represents the present value in constant dollars, *i* represents the discount rate, and n represents the length, in years, the cost was applied to the analyzed life cycle. This equation also related any applied maintenance costs to a present value.

The maintenance costs were set to a 5-year sliding scale that capped at a yearly cost of $2,500 (USD). This value represents any reactive maintenance costs that are not considered extensive but may include isolated patching or crack/joint sealing, where immediate action is required. Often times, the agency will self-perform these activities, unlike how the four evaluated preservation methods were fully bid-out projects. The calculation of these costs can be seen in Equation 2.

$$Maintenance\ Costs = \begin{pmatrix} (n/5) \times \$2{,}500 & When\ n \leq 5 \\ \$2{,}500 & When\ n > 5 \end{pmatrix} \qquad (2)$$

Where n is the year, and $2,500 (USD) is the cost for typical maintenance. The sliding scale represents the minor pavement care activities required immediately after a preservation as they progress to an increased quantity the longer it has been since the preservation.

Any remaining service life, such as those seen in the microsurfacing PCI example of Figure 5-1a and Figure 5-1b were related back to present value using Equation 3.

$$SLV = \left(\frac{n_r}{n_{SL}}\right) \times Preservation\ Costs \qquad (3)$$

Where SLV represent the present service life value, n_r represents the remaining length of service life after the analysis period, n_{SL} represents the full length of the determined service life, and preservation costs is representative of the historical average cost of said preservation method.

The sum of all construction and maintenance costs minus the remaining value of the remaining service life are represented as the net present value. This value was utilized to determine both the EUAC and cost/index value benefit, and the determination of these parameters is discussed in their corresponding results sections.

5.4 Results

This section includes the overall results for EAUC, costs/index value benefit, and sensitivity analyses of both interest rate and analysis period across all four pavement indices for each of the four flexible pavement preservation methods.

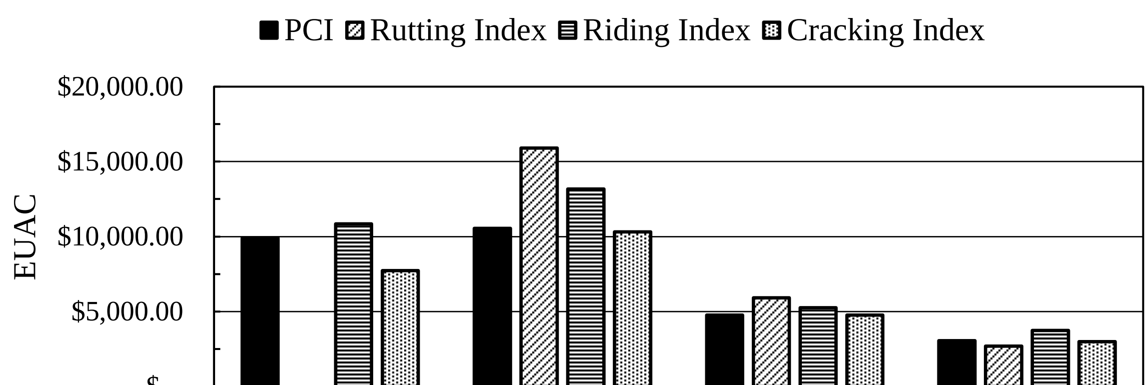
5.4.1 Equivalent Uniform Annual Costs

The EUAC of any given LCCA provides a yearly comparison tool to relate the costs of performing and maintaining the preservation method, as well as the return from any remaining service life at the end of the analysis period. Utilization of EUAC compared to NPV avoids the problem of finding appropriate common multiples of service lives (White et al. 2010). These values allow decision making to be made purely from an economic standpoint, while considering the length of service life extension, but without regard to the quantity of improvement experienced within any given pavement index. The calculation of EAUC can be seen in Equation 4.

$$EUAC = NPV\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \tag{4}$$

Where EUAC represents the equivalent uniform annual cost, NPV represent the net present value, *i* represents the discount rate, and n represents the length of the analysis period. Typical EUAC methods are directly related to the analysis period, but by utilizing this equation, the determined analysis period is bypassed (Pittenger et al. 2011).

Figure 5-2 shows the results of an LCCA with a service-life-length analysis period at the 1.3% suggested discount rate, according to the White House OMB circular (Mulvaney 2018). Crack/joint sealing resulted in the lowest EUAC values across all four pavement indices by at least $1,500 (USD), with an average EUAC of $3,115.47 (USD). Slurry sealing was the next lowest across all four indices, followed by microsurfacing and then patching, with average EUAC values of $5,178.37, $9,492.84, and $12,488.10 (USD), respectively. It should be noted that the rutting index data for microsurfacings was not applicable, as the evaluated rutting performance of the microsurfacings was worse than the pavement was showing beforehand. This likely was a result of the microsurfacings being primarily used as cracking remediation instead of rutting improvement. This may also indicate that project selection for microsurfacing may have not been ideal.



	Microsurfacin g	Patching	Slurry Seal	Crack/Joint Sealing
PCI	$9,910.26	$10,554.55	$4,763.49	$3,047.46
Rutting Index		$15,898.12	$5,920.58	$2,689.21
Riding Index	$10,835.84	$13,182.47	$5,256.99	$3,736.22
Cracking Index	$7,732.42	$10,317.25	$4,772.41	$2,989.00

Figure 5-2 *EUAC values from service life length LCCA (1.3% discount rate)*

5.4.2 Costs/Index Value Benefits

The cost per index value benefit uses the already determined EAUC values and divides them by the total quantity of index improvement observed by the preservation method. Since linear pavement performance trends were assumed for the LCCA, the total quantity of index improvement became the index value benefit times the duration of the analysis period. However, if non-linear functions were utilized, Equation 5 shows the method to determine the total index benefit.

$$IV * Year = \int_0^n f(Performance\ Curve)dn - \int_0^n f(Do\ Nothing\ Curve)dn \quad (5)$$

Where IV represents the "index value" of any given pavement index, IV*year represents the total index benefit, n represents the length of the analysis period, and *f*(Performance Curve) and *f*(Do Nothing Curve) represent any determined trendline that best describe the actual performance when the pavement is preserved or unpreserved, respectively.

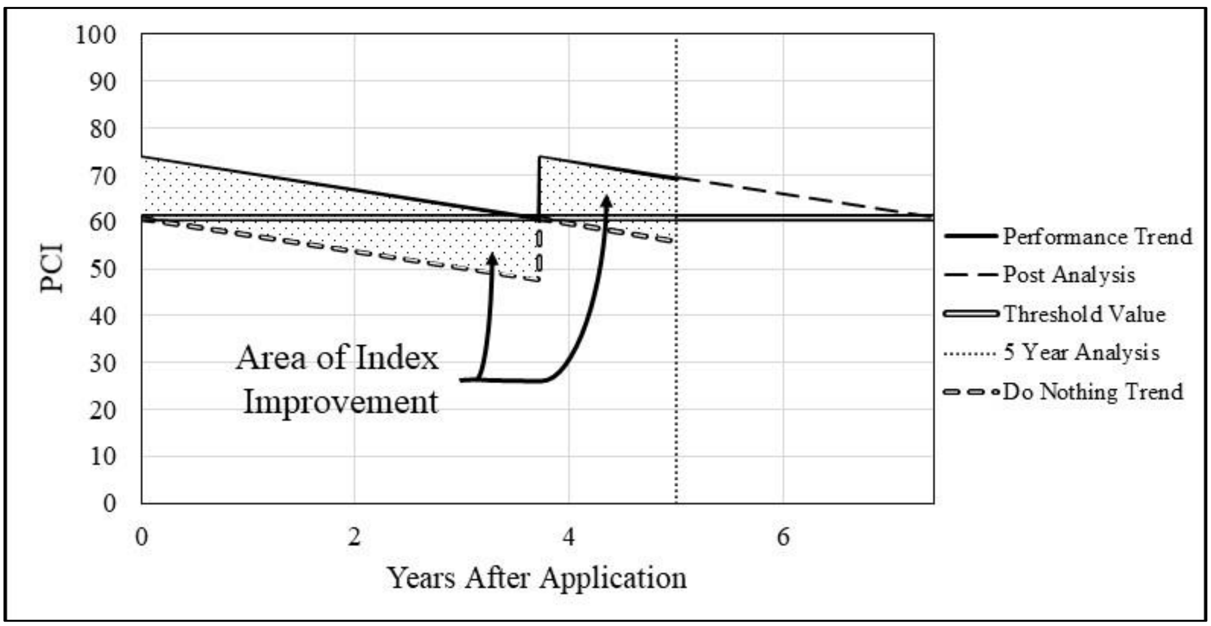


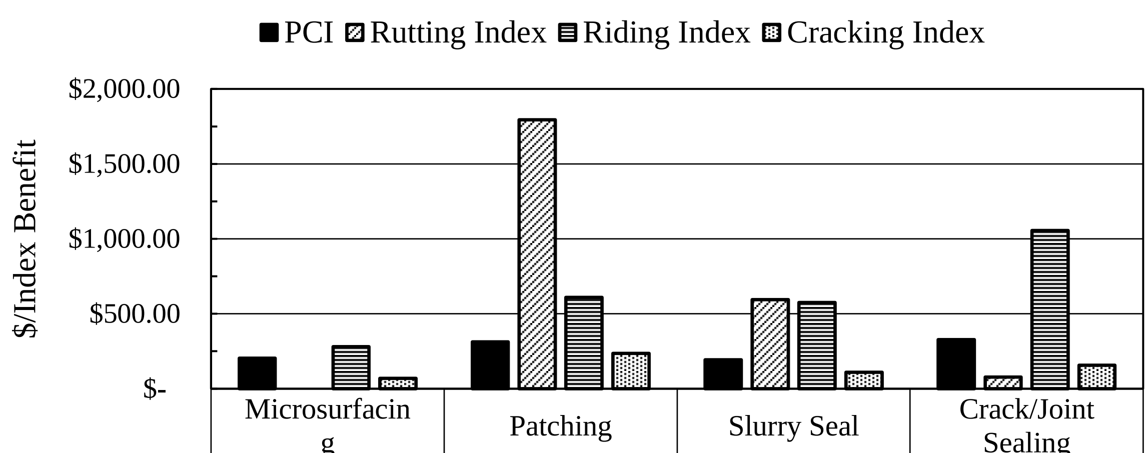
Figure 5-3 *Example determination of (Index Value*Year)*

Figure 5-3 shows an example of how the total quantity of index improvement was determined for the PCI a microsurfacing LCCA with an analysis period of 5 years. With both the performance trend and the do-nothing trend remaining parallel, as per the assumption when setting up the LCCA, the original 13.1-point improvement of the PCI remains constant, even after the second microsurfacing application. With the analysis period of 5 years, the total PCI index improvement was 65.5 PCI*Year, because of the 13.1 PCI improvement over 5 years.

With calculated units of IV*year, the division of the EUAC values by the total index improvements conveniently cancels out the year terms, and this relationship is seen in Equation 6.

$$\frac{\$}{IV} = \frac{EUAC}{Total\ Index\ Benefit} = \frac{\$*Year}{IV*Year} \quad (6)$$

Where $/IV represent the cost per index value benefit. This ratio describes the economic cost of each individual unit area of the total index benefit. Taking this a step beyond a typical EUAC analysis, the cost per index value benefit creates a smaller economic comparison of individual pavement index improvement costs. Figure 5-4 shows the results of the same LCCA in the previous section, with a service-life-length analysis period at the 1.3% suggested discount rate.



	Microsurfacing	Patching	Slurry Seal	Crack/Joint Sealing
PCI	$203.36	$312.64	$192.36	$326.84
Rutting Index		$1,793.97	$595.33	$76.75
Riding Index	$281.36	$608.52	$575.48	$1,054.83
Cracking Index	$69.34	$235.15	$110.11	$155.90

Figure 5-4 *$/Index Benefit values from service life length LCCA (1.3% discount rate)*

Of the four preservation methods, slurry sealing provided the lowest cost/PCI value benefit, with a value of $192.36 (USD). Microsurfacing was only eleven dollars higher, with both patching and crack/joint sealing coming it at over $300 (USD). The most economically efficient method for improving the rutting index, according to this analysis, was crack/joint sealing, with a cost of $76.75 (USD), which was more than $400 (USD) cheaper than the next best alternative of slurry sealing. Patching resulted in a cost nearing $2,000 (USD) per rutting index improvement, and the microsurfacing data for rutting index was not applicable. However, for both the riding and cracking indices, microsurfacing resulted in the lowest costs per index value improvements, with values of $281.36 (USD) and $69.34 (USD), respectively.

5.4.3 Sensitivity Analysis

Many parameters within a fixed LCCA come by means of interpreting various sources of data to make the best assumptions. Due to the nature of this approach, parameters such as the discount rate and analysis period have been known to significantly impact the results of a LCCA (Ferreira et al. 2012). In general, a sensitive parameter is one that greatly alters the values determined from the analysis. To test if a parameter is sensitive, the analysis is run multiple times, only changing the value of the variable at question.

Discount Rate Sensitivity

The first sensitivity analysis performed was looking at the impact of the discount rate on both the EUAC and cost per index value benefit. The LCCA was then run with analysis periods equal to the length of each index service life extension, only changing the discount rates. With 1.3% as the recommended discount rate for shorter analyses, the other tested values were 0.3%, 2.3%, and 4.3%. The results can be seen in Figure 5, where the EUAC and cost per index value benefits were compared to the values determined from the original discount rate of 1.3% as a percentage of the primary analysis.

Figure 5-5 *Sensitivity analysis of the discount rate*

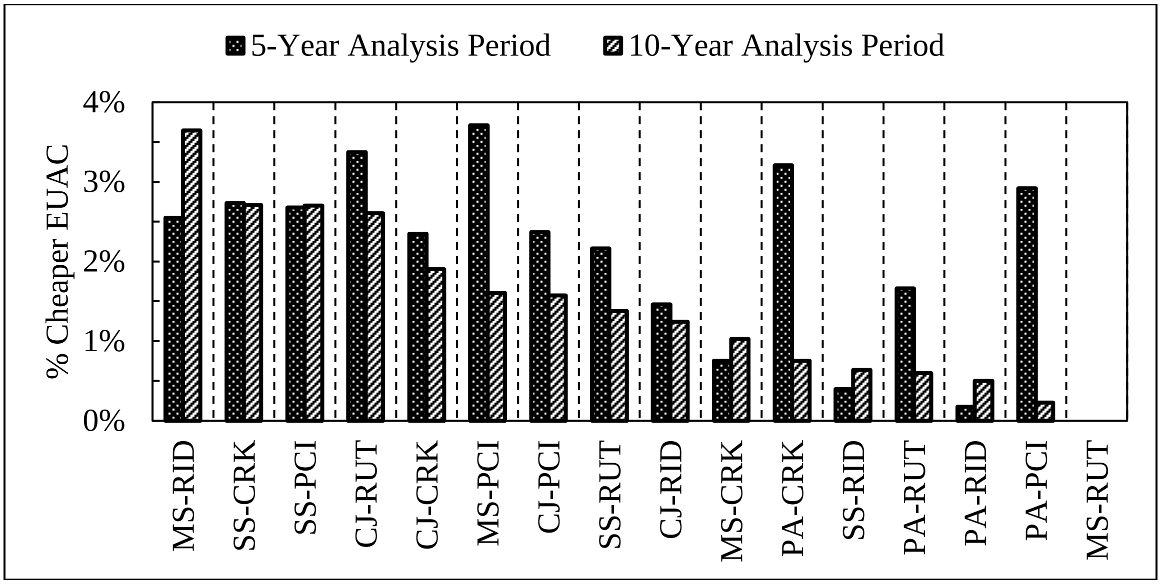
Conveniently, since linear pavement deterioration was assumed, the ratio of alternate discount rates to the 1.3% discount rates remains identical for both cost per index improvement and EUAC values. The result is a series of lines that pivot about the 1.3% discount rate values with inverse values from one side to the other. For example, the EUAC for the PCI analysis of a Slurry Sealing project with a discount rate of 1.3% is $4,763.49 (USD), while the 0.3% and 2.3% EUAC values are $4,693.34 (USD) and $4,834.17 (USD), respectively. Meanwhile, the cost per index benefit values from the same analysis for the discounts rates of 0.3%, 1.3%, and 2.3% were $189.52 (USD), $192.36 (USD), and $195.21 (USD) respectively. This relates to a 2% decrease with a discount rate of 0.3% and an increase of 2% with a discount rate of 2.3%. Similarly, the discount rate of 4.3% produces an increase of 6% for both EUAC and cost per index benefit values.

Figure 5-5 shows all inflated costs to remain between the bounds of 97-106% when evaluating the four different discount rates. Although the rutting data was not evaluated for microsurfacing projects, these projects showed the largest sensitivity to the discount rate for the other three indices, including the PCI, riding index, and cracking index. On the contrary, the crack/joint sealing projects showed the least sensitivity to the discount rate, likely a result of the shorter index service lives. The most separation between the four different flexible pavement preservation methods was seen in the cracking index.

Analysis Period Sensitivity

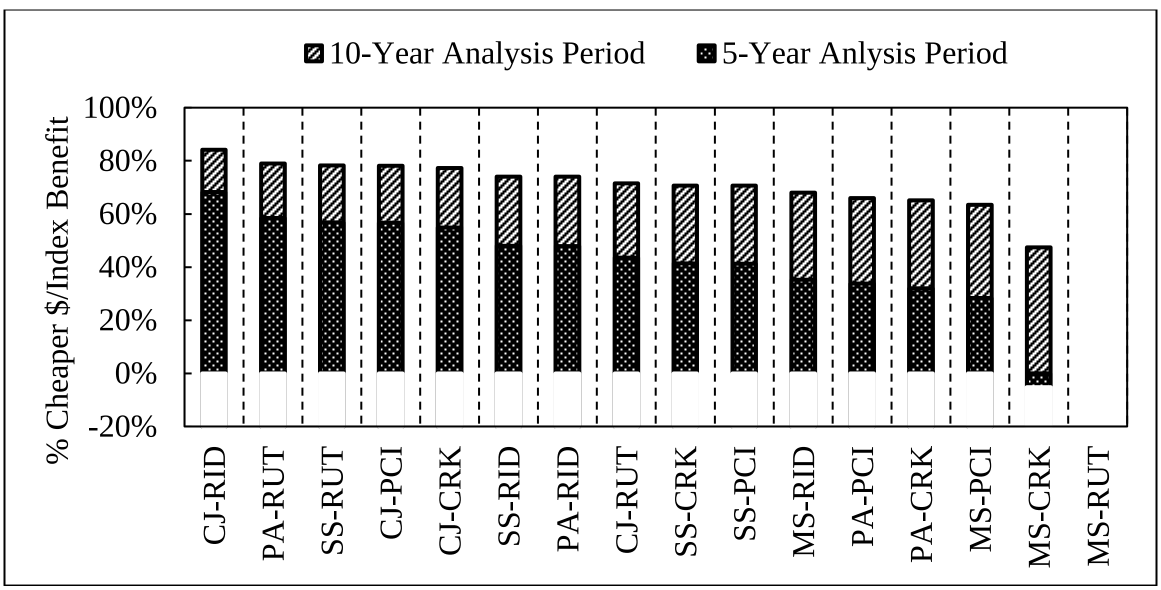
This sensitivity analysis takes the length of the analysis period an evaluates it at each index service life length, as well as a 5- and 10-year period. With the discount rate now fixed at 1.3%, the longer analysis periods allow time for multiple iterations of each preservation method to occur after the linear performance trends reach their threshold values. Figure 5-6 and Figure 5-7 show the percentage quantity that the 5- and 10-year analyses are cheaper than the index service life length analyses.

The resulting percentage quantity cheaper EUAC values, seen in Figure 5-6, are arranged from largest to smallest, left to right, according to the percentage quantity of the 10-year analysis. By a large margin, microsurfacing was shown to reduce the EUAC for its riding index by 3.65%. This high sensitivity is notable as the next largest 10-year analysis reduction was nearly an entire percent lower, at 2.71%, seen by the cracking index for slurry seals. Interestingly, the length of analysis period significantly changes which preservation methods appear the most sensitive to analysis length. For example, the microsurfacing rutting index saw the most change with a 10-year analysis but was below the 50th percentile with a 5-year analysis. The PCI and cracking index for patching displayed the some of the lower sensitivities at 10-years, but the 5-year analysis pushes them into the 4th and 3rd most sensitive EUAC values, respectively.



Note* MS – Microsurfacing, PA – Patching, SS – Slurry Sealing, CJ – Crack/Joint Sealing, PCI – PCI, RUT – Rutting Index, RID – Riding Index, and CRK – Cracking Index

Figure 5-6 *EUAC sensitivity analysis of analysis period length*



Note* MS – Microsurfacing, PA – Patching, SS – Slurry Sealing, CJ – Crack/Joint Sealing, PCI – PCI, RUT – Rutting Index, RID – Riding Index, and CRK – Cracking Index

Figure 5-7 *$/index benefit sensitivity analysis of analysis period length*

Figure 5-7 shows the results for the cost per index benefit parameter, arranged from largest to smallest, left to right, according to the percentage quantity of the 5-year analysis. The first noted items are the price decrease for crack/joint sealing in attempt to improve the rutting index. The 5- and 10-year analysis results in a 68% and 84% cheaper cost to improve the rutting index. On the other end of the spectrum, the microsurfacing 5-year analysis was the only result that was more costly than the service life length analysis. This is because the microsurfacing cracking index was the only evaluated index to have a service life greater than five years, with a value of 5.3 years. The 10-year analysis of this preservation's cracking index consequently was the least cost effective in benefiting the cracking index. Another pattern to note within Figure 7 is the relatively clustered preservation treatments. Crack/joint sealing indices were all above the 50th percentile in cost effectiveness, while microsurfacing indices were all below the 50th percentile. Patching and slurry sealing indices predominately filled the gaps in-between, with the noteworthy exception of the rutting index of both preservation methods taking the second and third most cost-effective index improvement. With observed reductions in cost by 42% and 71% for the 5- and 10-year analyses, respectively, there is no question as to whether the length of the analysis is highly sensitive.

5.5 Conclusions

The process for taking state-wide pavement information, through both historical bid tabulations and the Iowa DOT's PMS, and determining all of the necessary parameters to perform a fixed LCCA of four different pavement performance indices on four different flexible pavement preservation methods was performed and discussed in this study. By relating the lowest bid costs of microsurfacing, patching, slurry sealing, and crack/joint sealing from the last six years to a cost-per-kilometer basis, the average preservation costs were determined. The best fit performance trend fitting of the PMS data provided the individual threshold values, index value benefits, and service life extensions for the PCI, rutting index, riding index, and cracking index of each preservation method. Lastly, the discount rate suggested by the executive office of the president for constant dollar LCCA was the last necessary parameter needed to perform LCCA for these flexible pavement preservations.

Evaluation of the EUAC values showed patching to produce the highest values across all four pavement indices, followed by microsurfacing, slurry sealing, and crack/joint sealing, in that order. Meanwhile, the order of most to least expensive cost of construction was microsurfacing, patching, slurry sealing, and crack/joint sealing. This instantly provided an initial validation to the effectiveness of a LCCA, as basing the decision off construction costs would have resulted in the selection of patching over microsurfacing, while the EUAC values would have deterred that decision.

When evaluating the cost per index benefit, the lowest $/index benefit of PCI was seen by slurry sealing and was about $10 (USD) cheaper than microsurfacing, with both preservation methods costing around $200 (USD) per PCI benefit. Both crack/joint sealing and patching were around $320 (USD) per PCI benefit, with patching costing slightly less. Microsurfacing was the most cost effective for both the riding and cracking index benefits, while crack/joint sealing was substantially more cost effective than the other preservation methods for benefiting the rutting index.

Two different parameters were evaluated using a sensitivity analysis. These parameters were the discount rate and the length of the analysis period. Be evaluating the discount rates of 0.3%, 2.3%, and 4.3%, in conjunction with the current discount rate of

1.3%, it was observed that microsurfacing projects were the most sensitive to these variable rates, while crack/joint sealing projects were the least sensitive, across all four pavement indices. The smaller service life extensions and index benefits provided by the crack/joint sealing projects allowed less opportunity for the discount rate to significantly impact the cost per index benefit and EUAC values, whereas the microsurfacing projects had longer service lives with greater index value benefits. The cracking index was observed to yield the largest sensitivity for each preservation method. This was a culmination of the variability within the Iowa DOT’s PMS and the determined threshold and service life extension values.

The sensitivity analysis of the length of the analysis period showed confounding results in reducing the cost of each EUAC. When the 10-year analysis was compared to the index service life length analysis, the EUAC value for the microsurfacing riding index was by far the most sensitive, resulting in over 3.5% savings, but according to the 5-year analysis, the same treatment was significantly less sensitive, with just over 2.5% savings. Similar shifts were seen across all four preservation and index combinations. Figure 6 highlights how decision making according to a single analysis period has caveats and care should be taken to understand the uncertainty involved with specific assumptions.

5.6 Discussion

This study has shown the methods to properly implement a LCCA for flexible pavement preservation methods; however, this analysis on not limited to this application, and could be expanded into other PMS databases, performance criteria, and preservation methods (both flexible and rigid). The importance of this analysis is that the LCCA tool, while typically limited to considerable rehabilitation or reconstruction methods, can be adapted to less substantial preservation methods if the condition data has a high enough resolution to model the performance. The increasing economic pressures, in close relation to successful decision making make these long-term analyses highly beneficial to roadway agencies everywhere.

5.7 References

Bektas, F., Smadi, O., Al-Zoubi, M., 2014. Pavement Management Performance Modelling: Evaluating the Existing PCI Equations. *INTRANS Project 13-455*, Iowa DOT Project SPR RB14-013.

Ferreira, A., Santos, J., 2012. Life-Cycle Cost Analysis System for Pavement Management at Project Level: Sensitivity Analysis to the Discount Rate. *International Journal of Pavement Engineering.* 14 (7), 655-673.

Galehouse, L., 2002. Strategic Planning for Pavement Preventive Maintenance: Michigan Department of Transportation's "Mix of Fixes" Program. *TR News*, Number 219. March-April 2002. Transportation Research Board, Washington, D.C.

Iowa DOT, 2019a. Contracts, Bid Tabulations [online]. Iowa Department of Transportation. Available from: https://iowadot.gov/contracts/Historical-Completed-lettings/Bid-Tabs [Accessed 21 April 2019].

Iowa DOT, 2019b. Open Data PMIS 2017 [online]. Iowa Department of Transportation. Available from: http://data.iowadot.gov/datasets/48bfff7ffbfa4555bed8c374e44c9300_1 [Accessed 15 May 2018].

Mulvaney, M., 2018. Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses. *OMB Circular No. A*-94. Executive Office of the President, Office of Management and Budget. Washington, D.C.

Pittenger, D., Gransberg, D. D., Zaman, M., Riemer, C., 2011. Life-Cycle Cost-Based Pavement Preservation Treatment Design. *Transportation Research Record.* Volume 2235(1), 28–35.

Tseng, K., Lytton, R., 1989. Prediction of Permanent Deformation in Flexible Pavement Materials. *Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements*. Ed. Schreuders, H., Marek, C. ASTM International. West Conshohocken. 154-172.

Walls III, J., Smith, M., 1998. Life-Cycle Cost Analysis in Pavement Design. *Interim Technical Bulletin.* Federal Highway Administration Report FHWA-SA-98-079. Washington, DC.

White, J. A., Case, K.E., Pratt, D.E., 2010. *Principles of Engineering Economic Analysis*, 5th ed. John Wiley & Sons, Inc., Hoboken, N.J.

CHAPTER 6. CONCLUSIONS

6.1 General Conclusions

The overarching goal of this research was to develop a method for analyzing and evaluating a pavement management system database. With the use of the Iowa DOT data, modeling of the performance, followed by statistical and economic analysis, allowed for the determination of the effectiveness of microsurfacings, slurry seals, patching, and crack/joint sealing projects within the state of Iowa.

6.1.1 Pavement Performance

Utilization of either linear, second-order polynomial, of reflected logistic sigmoidal functions proved effective in describing the actual pavement responses to the preservation methods. While explained within an isolated study of slurry seal effectiveness, the service life extensions, index value benefits, and threshold values for the PCI, rutting, riding, and cracking indices were determined for all four preservation methods.

Microsurfacings yielded the largest PCI, riding, and cracking index service life extensions of 3.7, 3.3, and 5.3 years, respectively. The largest rutting index service life extension was determined for crack/joint sealing, likely a result of the sealant material occupying significant volumes of the wheel ruts.

The average threshold value across the four indices showed crack/joint sealing getting used the earliest, when its pavement indices were near values of 61.5. The average overall threshold value was 57.6, indicating non-ideal timing of these preservation methods. Regardless of timing, these preservation methods still displayed improvements across the board, with notable initial index value benefits of 21, 14, and 12.5 for the cracking index of microsurfacing, slurry sealing, and patching, respectively. The two other indices with initial index value benefits of at least 10 were the PCI and riding index of microsurfacings. Interestingly, the only instance of worsened performance after preservation was the rutting index for microsurfacings. This is indicative of significant rutting distresses stemming from material or subbase shortcomings.

6.1.2 Influential Variables on Performance

When breaking out the initial index benefits of the microsurfacing projects according to AADT value either less than or greater than 10,000, clear groupings were identified. Speculation that higher trafficked roads receive better quality materials and faster reaction times was proven by the threshold values for PCI. Higher traffic levels resulted in preservations when the preservation threshold was at an average value of 68.5, while lower trafficked pavements received treatment at an average threshold value of 55.6. Similar trends were identified for the other three performance indices.

The split plot repeated measures statistical analysis of all four preservation methods brought light to a few different aspects of performance modeling. First, this statistical approach is highly effective at reducing the very large variabilities between pavement sections that are receiving the same treatment. Second, the effect of the preservations produced almost entirely parallel plots between preserved and unpreserved pavements, showing the rate of deterioration after preservation to remain similar to the rate before preservation. Notable exceptions were the slurry sealing and crack/joint sealing cracking indices, where the rate of deterioration increased after application of the preservation methods. Lastly, every single index for all four preservation types had statistically lower relative year two values compared to relative year zero values for both preserved an unpreserved pavement, indicating significant deterioration within two years of application.

6.1.3 Life Cycle Cost Analysis

The results of the LCCA showed crack/joint sealing to have the lowest EAUC values, followed by slurry sealing, microsurfacing, and patching, in that order. However, when taking the analysis a step further and determine the cost per PCI value benefit, slurry sealing and microsurfacing were substantially cheaper than patching and crack/joint sealing. The cost per rutting index benefit showed crack/joint sealing to provide the lowest cost by a significant margin. In addition, a sensitivity analysis was performed on the discount rate and analysis period length. The shorter index service life extensions showed lower sensitivity to the discount rate than longer service life extensions. The length of the analysis period showed the wide variability associated with the analysis length and the importance of evaluating varying analysis period lengths when performing LCCA.

6.2 Comparisons to an HMA Overlay

A last comparison to the research is seen in this section and was isolated to drive home the importance of implementing successful pavement preservation programs. Table 6-1 takes the construction costs and average PCI service life extension for a single lane-mile of the four preservation methods and compares them to the values for a thin HMA overlay. The costs and PCI service life values for the overlay were averages from the FHWA study performed by Wu et al. (2010).

By dividing the preservation cost per lane-mile by the HMA overlay cost per lane-mile per year, the result is the length of time that the preservation needs to extend the service life by to remain economically similar. All four methods resulted in at least 1.6 years of remaining service life after paying for themselves. The 13-year service life of the HMA overlay was then divided by the average PCI service life extensions and then multiplied by the remaining service life to provide the total service life gained by repeating the preservation method instead of performing the overlay.

Table 6-1 *Service life extension benefits through preservation*

Project Type	$/Lane Mile	$/Mile Year	Average PCI Service Life Extension (Years)	Required Service Life to Pay for Its Own Construction (Years)	Remaining Service Life (Years)	Gained Service Life Extension with Repeated Preservation Using Same Overlay Budget (Years)
Thin HMA Overlay (1.5")	$139,539	$10,734	13	-	-	-
Microsurfacing	$19,510	$5,273	3.7	1.8	1.9	6.7
Patching	$19,399	$5,705	3.4	1.8	1.6	6.1
Slurry Seal	$6,841	$2,280	3.0	0.6	2.4	10.4
Crack/Joint Sealing	$2,986	$1,357	2.2	0.2	2.0	11.8

The results speak for themselves, with minimum gained service lives of 6.1 years. Prior to any objections, it is understood that these preservation methods cannot be repeated constantly without significant interaction, such as milling. However, with appropriate combinations of these preservation methods, there are real possibilities of observing significant gains in service life extensions.

6.3 Contribution to literature

Chapter 2, based off the paper titled "Analytical Methods to Determine Effectiveness of Slurry Seals in Wet/Freeze Climates Using a Pavement Management Information System," introduced the methods involved in modelling pavement performance. By taking indexed data, deterioration trends were modeled using practical engineering concepts. Three different curves were evaluated according to the least sum of the squared error and showed reasonable predictions of the actual observed performance and continued deterioration performance.

Chapter 3, based off the paper titled “Microsurfacing Performance Evaluation Using a Locally Sourced Pavement Management Information System,” applied the methods developed in chapter 2 to a collection of microsurfacing projects. The importance of preservation timing, as well as the impact of higher trafficking, were seen when comparing the analytical benefits from the performance models. These identifiable behaviors highlighted the strength of the performance model and its potential applications for furthered analysis.

Chapter 4, based off the paper titled “Retrospective Split-Plot Statistical Analysis to Determine Pavement Preservation Performance,” proved that large quantities of variability from one pavement section to another could be significantly reduced. This reduced variability then provides better estimations for the actual pavement response to the preservation methods. As this retrospective analysis was successful in isolating these performance results, the ability to include any project into an analysis, regardless of its pavement structure, could be a possibility.

Lastly, chapter 5, based on the paper titled “Life-Cycle Cost Analysis Based on State-Sourced Flexible Pavement Preservation Performance Data,” ultimate proved that an economic analysis of different pavement preservation methods could be approached in greater depth with a life-cycle cost analysis. Typically, this method is utilized for longer service life pavement treatments, such as rehabilitation or reconstruction. However, application of sound economic analytics allowed for comparisons between equivalent annual uniform costs and index value improvements. The results from this paper further confirmed the successful performance model developed to analyze the Iowa DOT pavement management information system.

6.4 Suggestions for Future Research

First and foremost, this entire research effort has been contingent upon the quantity and quality of the data within the Iowa DOT's pavement management system. For any agencies with interest in performing their own pavement preservation analysis, it is highly suggested to invest significantly into the data collection and deposition. Having trustworthy values is half of the battle. The other half lies within having preservation projects to evaluate. A significant setback to the analysis of this data came from smaller quantities of projects with collected data.

While this research has taken in-depth looks at the PCI, rutting, riding, and cracking indices, analysis is not limited to these performance indicators. Whether creating similarly convenient metrics, or simply running the analysis on non-indexed data, the only limitation is having the ability to fit realistic performance trends. With numbers all within similar magnitudes, this condition could easily be met.

The historical cost data for this research was substantial enough to meet the requirements for confident analysis. Similar to the data collection process, larger ranges of historical cost data could also be implemented as predictive models themselves. The cost data could first be converted to constant dollars. Then the rate of change could be used to model an estimated forward trend. These changing constant dollar values would them be used as the costs of future treatments when performing LCCA.

Lastly, exploration of additional variables on pavement performance could identify trends that would otherwise go unnoticed. Use of artificial intelligence through an artificial neural network could take some of the self modelled performance data to "learn" from. Then, multiple input factors from the PMS could be run through the artificial neural network in attempt to identify these hidden trends. Implementation of this idea would require a very clean dataset, with realistic values within every input and output category.

REFERENCES

AASHTO. (1993). Design Related Project Level Pavement Management, *AASHTO Guide for Design of Pavement Structures* (pp. Part I 31-39). Washington, D.C.: American Association of State Highway and Transportation Officials.

Abdeblaty, A, Jeong, D, and Smadi, O, "Barriers to Implementing Data-Driven Pavement Treatment Perormance Evaluation Process." Journal of Transportation Engineering, American Society of Civil Engineers. Volume 144, Issue 1. March 2018.

Adbi, H., Williams, L., 2010. Tukey's Honestly Significant Difference (HSD) Test. *Encyclopedia of Research Design*, Thousand Oaks, California: Sage.

ASTM (2011) "Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys." D6433, ASTM, Philadelphia, Pa.

Bektas, F, Smadi, O, Al-Zoubi, M. "Pavement Management Performance Modeling: Evaluating the Existing PCI Equations." INTRANS Project 13-455, Iowa DOT Project SPR RB14-013. December 2014.

Brown, E. R. (1988). *Preventative Maintenance of Asphalt Concrete Pavements*, NCAT Report 88-01. Presented at the Transportation Research Board Annual Meeting.

Broughton, B., Lee, S., and Kim, Y., 2012. 30 Years of Microsurfacing: A Review. International Scholarly Research Network, Vol. 2012, Article 279643.

Buss, A., et. al., 2018. Extracting More from Dynamic Modulus Data Using Split-Plot Repeated Measures Analysis. *ASTM Journal of Testing and Evaluation*, 46(1), 351–364.

Cobb, G. W., 2014. The Principle of Blocking. *Introduction to Design and Analysis of Experiments*, Daryaganj, New Delhi: Wiley, 243-309.

Dinov, I. D., 2019. *Statistics Online Computational Resource: F Distribution Tables* [online]. University of California Los Angeles Department of Statistics. Available from: http://www.socr.ucla.edu/Applets.dir/F_Table.html [Accessed 22 Apr 2019].

Dong, Q., Huang, B. H. (2012). Evaluation of Effectiveness and Cost-Effectiveness of Asphalt Pavement Rehabilitations Utilizing LTPP Data. *Journal of Transportation Engineering ASCE*. 138. No 6.

Dwight-Hixon, C., and Ooten, D. A. (1993). "Nine years of microsurfacing in Oklahoma." Transportation Research Record. 1392, Transportation Research Board, National Research Council, Washington D.C., 13–19.

Erwin, T. and S.L. Tighe, "Safety Effect of Preventive Maintenance: A Case Study of Microsurfacing," Transportation Research Record: Journal of the Transportation Research Board, No. 2044, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 79–86.

Ferreira, A., Santos, J., 2012. Life-Cycle Cost Analysis System for Pavement Management at Project Level: Sensitivity Analysis to the Discount Rate. *International Journal of Pavement Engineering.* 14 (7), 655-673.

FHWA. (2003). Introduction to the LTPP Information Management System (IMS) [Report]. Retrieved from https://www.fhwa.dot.gov/publications/research/ infrastructure/ pavements/ltpp/reports/ 03088/01.cfm

FHWA. (2009). Long-Term Pavement Performance Program [Brochure]. Retrieved from https://infopave.fhwa.dot.gov/InfoPave_Repository/Reports/A10%20%20 Reports %20and%20Briefs/A10_20%20-%20Resource%20Documents/A10_20_20 %20-%20Brochures/FHWA_HRT-15-%20018.pdf

FHWA. (2014). *Distress Identification Manual for the Long-Term Pavement Performance Program*. Publication No. FHWA-HRT-13-092.

Forough, S. A., Nejad, F. M., Khodaii, A. (2015). An Investigation of Different Fitting Functions to Accurately Model the compressive Relaxation Modulus Master Curve of Asphalt Mixes. *Road Materials and Pavement Design*, 16, pp. 767-783.

Galehouse, L., 2002. Strategic Planning for Pavement Preventive Maintenance: Michigan Department of Transportation's "Mix of Fixes" Program. *TR News*, Number 219. March-April 2002. Transportation Research Board, Washington, D.C.

Galehouse, L., Moulthrop, J. S., Hicks, R. G. 2003. Principles of Pavement Preservation Definitions, Benefits, Issues, and Barriers. Transportation Research Record. 228.

Geiger, D. R. (2005, September 12). Pavement Preservation Definitions [Memorandum]. Retrieved from https://www.fhwa.dot.gov/pavement/preservation/ 091205.cfm.

Hajj, E. Y., Loria, L., Sebaaly, P. E., Borroel, C. M., Leiva, P. (2011). Optimum Time for Application of Slurry Seal to Asphalt Concrete Pavements. *Transportation Research Record*, 2235, pp. 66-81.

Hudson, W. R., Haas, R., Pedigo, R. D., 1997. Pavement Management System Development. NCHRP Report 215, Transportation Research Board, Washington, D.C.

Iowa DOT. (2017). Iowa DOT Open Data. Retrieved from http://data.iowadot.gov/data sets/pmis-2015.

Iowa DOT, 2019a. Contracts, Bid Tabulations [online]. Iowa Department of Transportation. Available from: https://iowadot.gov/contracts/Historical-Completed-lettings/Bid-Tabs [Accessed 21 April 2019].

Iowa DOT, 2019b. Open Data PMIS 2017 [online]. Iowa Department of Transportation. Available from: http://data.iowadot.gov/datasets/48bfff7ffbfa4555bed8c374e44c9300_1 [Accessed 15 May 2018].

ISSA. (2010). *High Performance Slurry Systems Inspector's Manual*. Annapolis, MD: International Slurry Surfacing Association.

Johnson, D., et. al., 2000. Cost-Effectiveness of Crack Sealing Materials and Techniques for Asphalt Pavements. Transportation Research Record, 1697, 31-40.

Labi, S, Lamptey, G, and Kong, S, "Effectiveness of Microsurfacing Treatments," Journal of Transportation Engineering, American Society of Civil Engineers. Volume 133, Issue 5. May 2007.

Mulvaney, M., 2018. Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses. *OMB Circular No. A*-94. Executive Office of the President, Office of Management and Budget. Washington, D.C.

NCHRP, 2014. Pavement Patching Practices. National Cooperative Highway Research Program, Synthesis 463. Transportation Research Board. Washington, D.C.

Park, K., et. al., 2007. Applicability of the International Roughness Index as a Predictor of Asphalt Pavement Condition. *ASCE Journal of Transportation Engineering*, 133(12), 706-709.

Pittenger, D., Gransberg, D. D., Zaman, M., Riemer, C., 2011. Life-Cycle Cost-Based Pavement Preservation Treatment Design. *Transportation Research Record.* Volume 2235(1), 28–35.

Tseng, K., Lytton, R., 1989. Prediction of Permanent Deformation in Flexible Pavement Materials. *Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements*. Ed. Schreuders, H., Marek, C. ASTM International. West Conshohocken. 154-172.

Van Genuchten, M. T., Gupta, S. K. (1993). A Reassessment on the Crop Tolerance Response Function. Journal of the Indian Society of Soil Science, 41, pp. 730-737.

Walls III, J., Smith, M., 1998. Life-Cycle Cost Analysis in Pavement Design. *Interim Technical Bulletin.* Federal Highway Administration Report FHWA-SA-98-079. Washington, DC.

White, J. A., Case, K.E., Pratt, D.E., 2010. *Principles of Engineering Economic Analysis*, 5th ed. John Wiley & Sons, Inc., Hoboken, N.J.

Wu, Z., Groeger, J., Simpson, A., and Hicks, G. 2010. Performance Evaluation of Various Rehabilitation and Preservation Treatments. Report FHWA-HIF-10-020, Federal Highway Administration, Washington, D.C.

APPENDIX. PAVEMENT INDEX PERFORMANCE TRENDLINE DATA

The contents of this appendix include the determined, best-fit, performance-based trend lines and coefficients for each of the four evaluated pavement indices within the chapter two study of thirteen slurry sealing projects. As mentioned within the body of this document, the primary source of data was contained within the Iowa DOT's PMIS database. This appendix substitutes a very lengthy appendix by displaying a smaller subset of the overall data to show the background processes. The methods to derive at these values is fully explained within the body text.

Coefficients of Each Best-Fit Trendline

MP-006-6(701)209--76-48

(PCI Do Nothing Function: RLS; a=0.15, b=1.11, c=0)

(PCI Observed Performance Function: RLS; a=0.08, b=1.40, c=0.87)

(Rutting Index Do Nothing Function: RLS; a=0, b=0.22, c=0.08)

(Rutting Index Observed Performance Function: RLS; a=0.17, b=1.05, c=0.85)

(Riding Index Do Nothing Function: RLS; a=0.01, b=1.53, c=0.21)

(Riding Index Observed Performance Function: RLS; a=0.12, b=0.78, c=0.25)

(Cracking Index Do Nothing Function: Polynomial; a=1.70, b=22.6, c=24.2)

(Cracking Index Observed Performance Function: Polynomial; a=1.51, b=0, c=89.0)

MP-059-3(703)140--76-47

(PCI Do Nothing Function: RLS; a=0.05, b=1.44, c=0.39)

(PCI Observed Performance Function: RLS; a=0.31, b=0.60, c=0.56)

(Rutting Index Do Nothing Function: RLS; a=0.01, b=1.72, c=0.22)

(Rutting Index Observed Performance Function: RLS; a=0.00, b=3.73, c=0.64)

(Riding Index Do Nothing Function: Linear; a=0, b=2.64, c=44.3)

(Riding Index Observed Performance Function: Polynomial; a=0.51, b=0, c=47.1)

(Cracking Index Do Nothing Function: Linear; a=0, b=3.87, c=72.5)

(Cracking Index Observed Performance Function: Linear; a=0, b=4.78, c=68.2)

MP-059-4(703)20--76-36

(PCI Do Nothing Function: Linear; a=0, b=2.27, c=71.5)

(PCI Observed Performance Function: RLS; a=0.10, b=0.78, c=1.21)

(Rutting Index Do Nothing Function: RLS; a=0.11, b=0.79, c=0.82)

(Rutting Index Observed Performance Function: RLS; a=0.00, b=2.47, c=1.22)

(Riding Index Do Nothing Function: RLS; a=0.23, b=0.37, c=0.64)

(Riding Index Observed Performance Function: RLS; a=0.13, b=0.70, c=0.73)

(Cracking Index Do Nothing Function: Linear; a=0, b=4.37, c=72.7)

(Cracking Index Observed Performance Function: RLS; a=0.70, b=0.26, c=2.05)

MP-067-6(705)48--76-23

(PCI Do Nothing Function: RLS; a=0.01, b=1.91, c=0.53)

(PCI Observed Performance Function: RLS; a=0.17, b=0.90, c=0.59)

(Rutting Index Do Nothing Function: Linear; a=0, b=0, c=62.8)

(Rutting Index Observed Performance Function: RLS; a=0.11, b=1.03, c=0.67)

(Riding Index Do Nothing Function: Polynomial; a=0.00, b=0.86, c=55.4)

(Riding Index Observed Performance Function: RLS; a=0.08, b=1.02, c=0.25)

(Cracking Index Do Nothing Function: Linear; a=0, b=5.37, c=58.0)

(Cracking Index Observed Performance Function: RLS; a=0.29, b=0.83, c=0.92)

MP-130-6(702)14--76-82

(PCI Do Nothing Function: Linear; a=0, b=5.81, c=26.5)

(PCI Observed Performance Function: Polynomial; a=0.33, b=0, c=47.1)

(Rutting Index Do Nothing Function: RLS; a=0, b=0.18, c=0.18)

(Rutting Index Observed Performance Function: Linear; a=0, b=1.47, c=52.8)

(Riding Index Do Nothing Function: RLS; a=0.00, b=2.55, c=0)

(Riding Index Observed Performance Function: Linear; a=0, b=1.37, c=46.8)

(Cracking Index Do Nothing Function: Polynomial; a=0, b=11.9, c=0)

(Cracking Index Observed Performance Function: Polynomial; a=0.90, b=0, c=47.7)

MP-136-6(701)73--76-31

(PCI Do Nothing Function: Linear; a=0, b=2.59, c=33.2)

(PCI Observed Performance Function: Polynomial; a=0, b=0, c=35.7)

(Rutting Index Do Nothing Function: RLS; a=0.09, b=0.82, c=0)

(Rutting Index Observed Performance Function: RLS; a=0.29, b=0.01, c=0.01)

(Riding Index Do Nothing Function: Linear; a=0, b=1.98, c=22.6)

(Riding Index Observed Performance Function: Polynomial; a=0.28, b=0.52, c=20.4)

(Cracking Index Do Nothing Function: Linear; a=0, b=4.77, c=25.2)

(Cracking Index Observed Performance Function: RLS; a=0.18, b=0, c=0.14)

MP-140-3(702)10--76-75

(PCI Do Nothing Function: RLS; a=0.27, b=0.79, c=0.23)

(PCI Observed Performance Function: RLS; a=0.16, b=0.94, c=0.49)

(Rutting Index Do Nothing Function: RLS; a=0.11, b=0.33, c=0.45)

(Rutting Index Observed Performance Function: RLS; a=0.02, b=2.05, c=0.56)

(Riding Index Do Nothing Function: Linear; a=0, b=2.49, c=58.3)

(Riding Index Observed Performance Function: RLS; a=0.00, b=2.68, c=0.51)

(Cracking Index Do Nothing Function: Linear; a=0, b=5.63, c=60.7)

(Cracking Index Observed Performance Function: Linear; a=0, b=3.44, c=54.2)

MP-141-4(705)115--76-39

(PCI Do Nothing Function: Polynomial; a=0.37, b=5.98, c=52.2)

(PCI Observed Performance Function: Polynomial; a=0, b=0, c=64.3)

(Rutting Index Do Nothing Function: Linear; a=0, b=0, c=66.2)

(Rutting Index Observed Performance Function: RLS; a=0.41, b=0.33, c=0.91)

(Riding Index Do Nothing Function: Linear; a=0, b=3.49, c=36.5)

(Riding Index Observed Performance Function: RLS; a=0.13, b=0, c=0.00)

(Cracking Index Do Nothing Function: RLS; a=0.00, b=3.51, c=1.48)

(Cracking Index Observed Performance Function: Polynomial; a=0, b=0, c=82.1)

MP-148-4(709)22--76-87

(PCI Do Nothing Function: Linear; a=0, b=1.24, c=69.1)

(PCI Observed Performance Function: RLS; a=0.34, b=0.13, c=0.96)

(Rutting Index Do Nothing Function: Linear; a=0, b=0.04, c=75.3)

(Rutting Index Observed Performance Function: RLS; a=0.28, b=0.49, c=0.99)

(Riding Index Do Nothing Function: RLS; a=0.16, b=0.66, c=0)

(Riding Index Observed Performance Function: Polynomial; a=0.01, b=0.00, c=52.8)

(Cracking Index Do Nothing Function: Linear; a=0, b=2.16, c=77.0)

(Cracking Index Observed Performance Function: Polynomial; a=0, b=0, c=69.2)

MP-151-6(705)11--76-48

(PCI Do Nothing Function: RLS; a=0.02, b=1.82, c=1.11)

(PCI Observed Performance Function: RLS; a=0.11, b=0.68, c=1.06)

(Rutting Index Do Nothing Function: RLS; a=0.14, b=1.25, c=0.20)

(Rutting Index Observed Performance Function: RLS; a=0.32, b=0.01, c=0.23)

(Riding Index Do Nothing Function: RLS; a=0.06, b=1.20, c=0.79)

(Riding Index Observed Performance Function: RLS; a=0.05, b=1.70, c=1.05)

(Cracking Index Do Nothing Function: Linear; a=0, b=3.21, c=76.3)

(Cracking Index Observed Performance Function: RLS; a=0.20, b=0.23, c=1.80)

MP-182-3(701)0--76-60

(PCI Do Nothing Function: RLS; a=0.06, b=1.54, c=0)

(PCI Observed Performance Function: RLS; a=0.70, b=0.04, c=0.56)

(Rutting Index Do Nothing Function: Polynomial; a=0.21, b=3.94, c=48.7)

(Rutting Index Observed Performance Function: RLS; a=0.00, b=3.40, c=0.42)

(Riding Index Do Nothing Function: Linear; a=0, b=0.08, c=61.0)

(Riding Index Observed Performance Function: RLS; a=0.02, b=1.48, c=0.22)

(Cracking Index Do Nothing Function: Linear; a=0, b=10.2, c=30.9)

(Cracking Index Observed Performance Function: Linear; a=0, b=2.24, c=42.4)

MP-220-6(705)1--76-48

(PCI Do Nothing Function: RLS; a=0.19, b=0.55, c=0.41)

(PCI Observed Performance Function: RLS; a=0.44, b=0.06, c=0.91)

(Rutting Index Do Nothing Function: Linear; a=0, b=0.04, c=69.1)

(Rutting Index Observed Performance Function: Polynomial; a=0, b=0, c=67.6)

(Riding Index Do Nothing Function: RLS; a=0.05, b=0.93, c=0)

(Riding Index Observed Performance Function: RLS; a=0.49, b=0, c=0.60)

(Cracking Index Do Nothing Function: Linear; a=0, b=2.35, c=69.6)

(Cracking Index Observed Performance Function: Polynomial; a=0, b=0, c=57.3)

MPIN-029-3(714)106--0N-67

(PCI Do Nothing Function: Linear; a=0, b=6.59, c=66.9)

(PCI Observed Performance Function: RLS; a=0.56, b=0.06, c=2.08)

(Rutting Index Do Nothing Function: Linear; a=0, b=12.3, c=60.1)

(Rutting Index Observed Performance Function: Polynomial; a=0.05, b=0.01, c=15.0)

(Riding Index Do Nothing Function: Linear; a=0, b=2, c=72)

(Riding Index Observed Performance Function: Polynomial; a=0, b=0, c=85.7)

(Cracking Index Do Nothing Function: Linear; a=0, b=0.33, c=95.0)

(Cracking Index Observed Performance Function: Polynomial; a=0.09, b=0.01, c=82.5)

Pavement Index Graphs

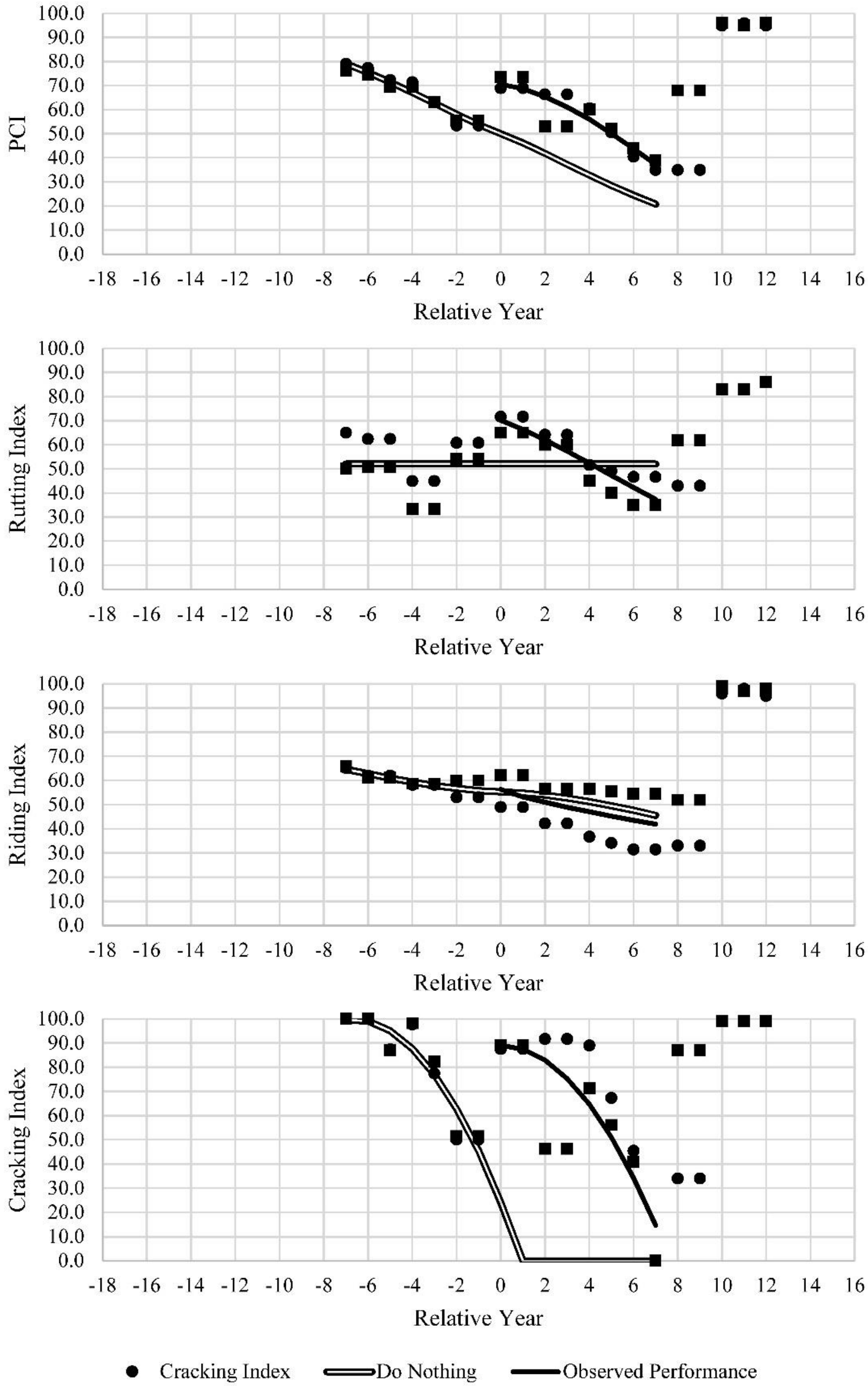


Figure 0-1 *Performance curves for MP-006-6(701)209--76-48*

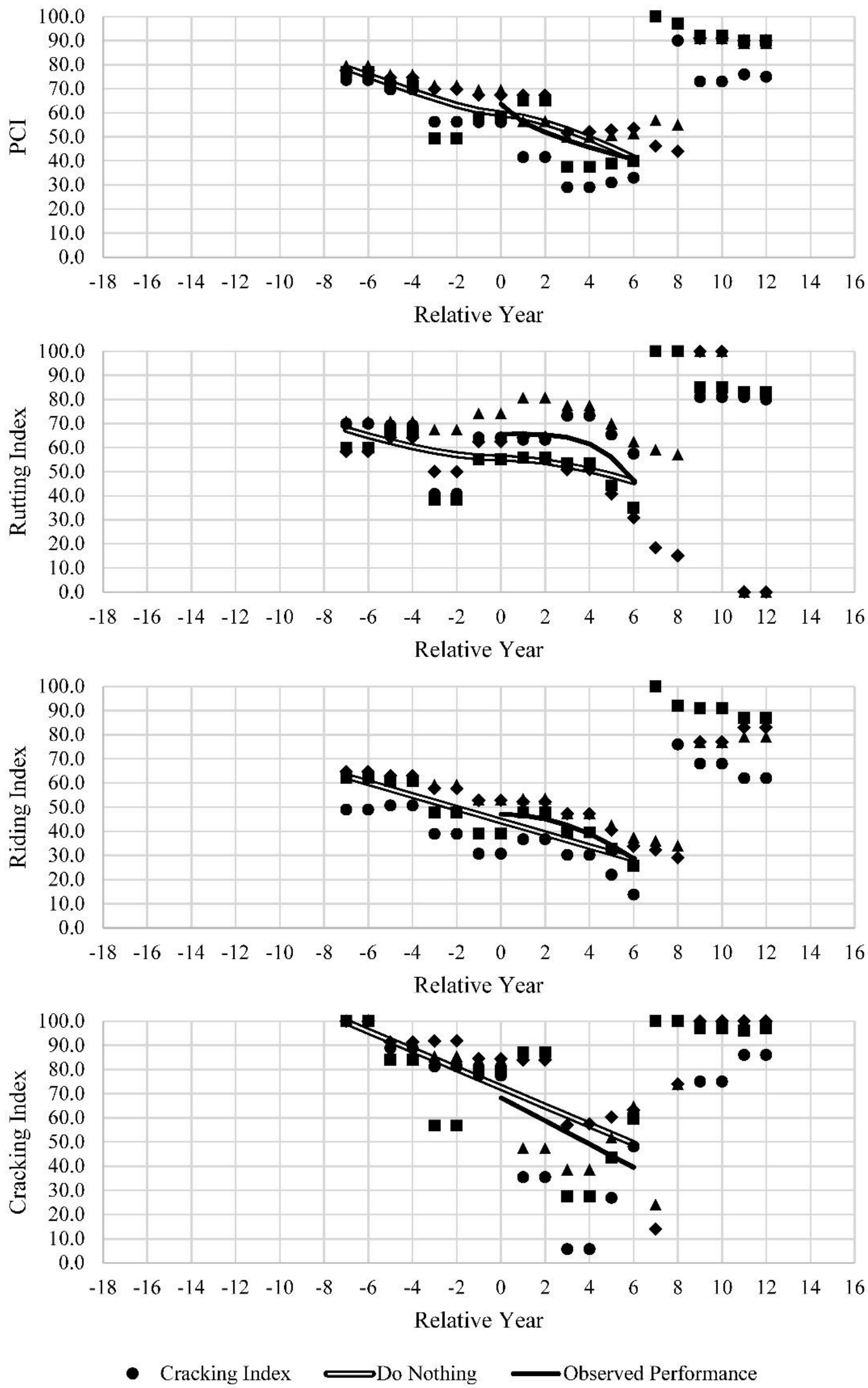


Figure 0-2 *Performance curves for MP-059-3(703)140--76-47*

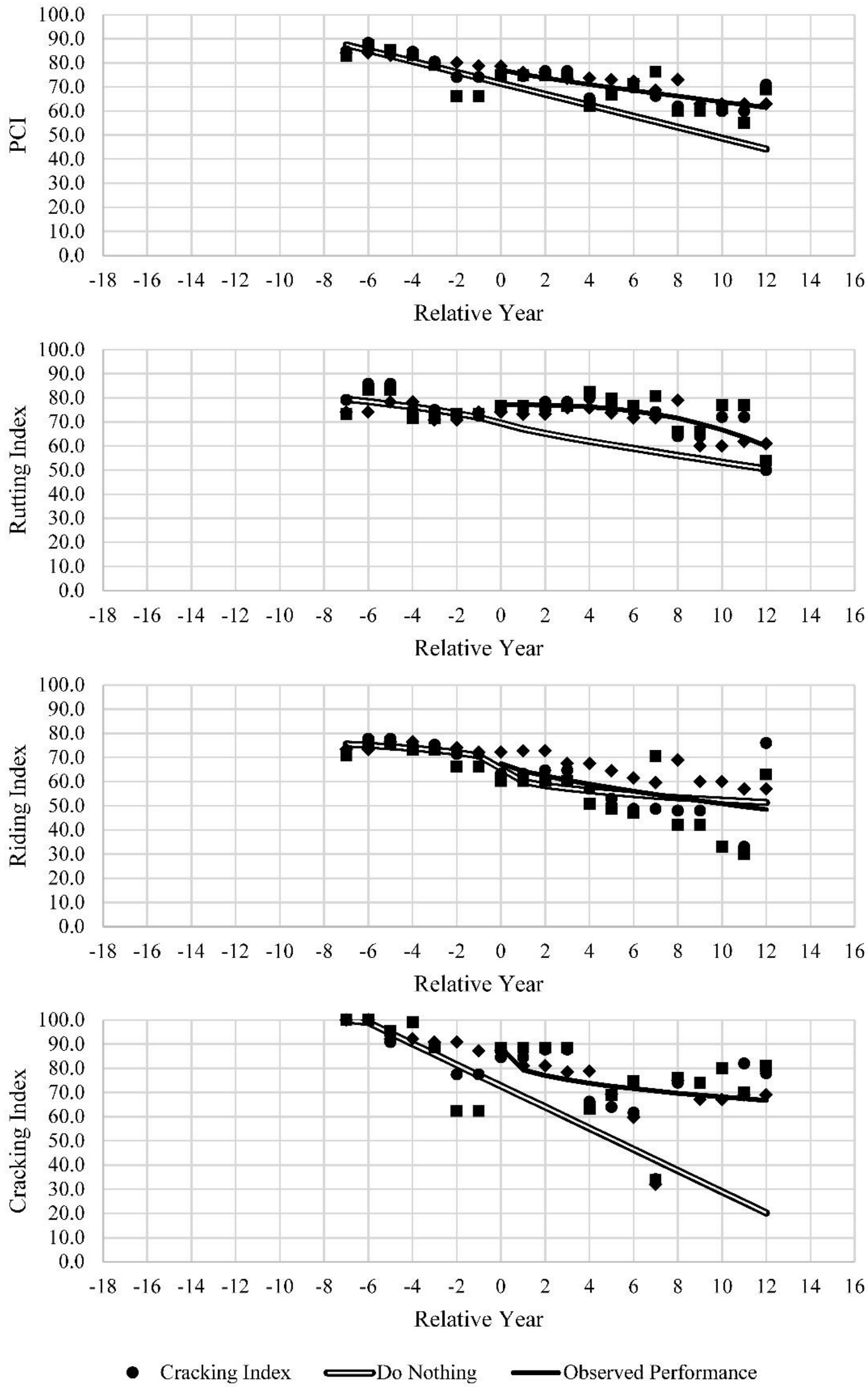


Figure 0-3 *Performance curves for MP-059-4(703)20--76-36*

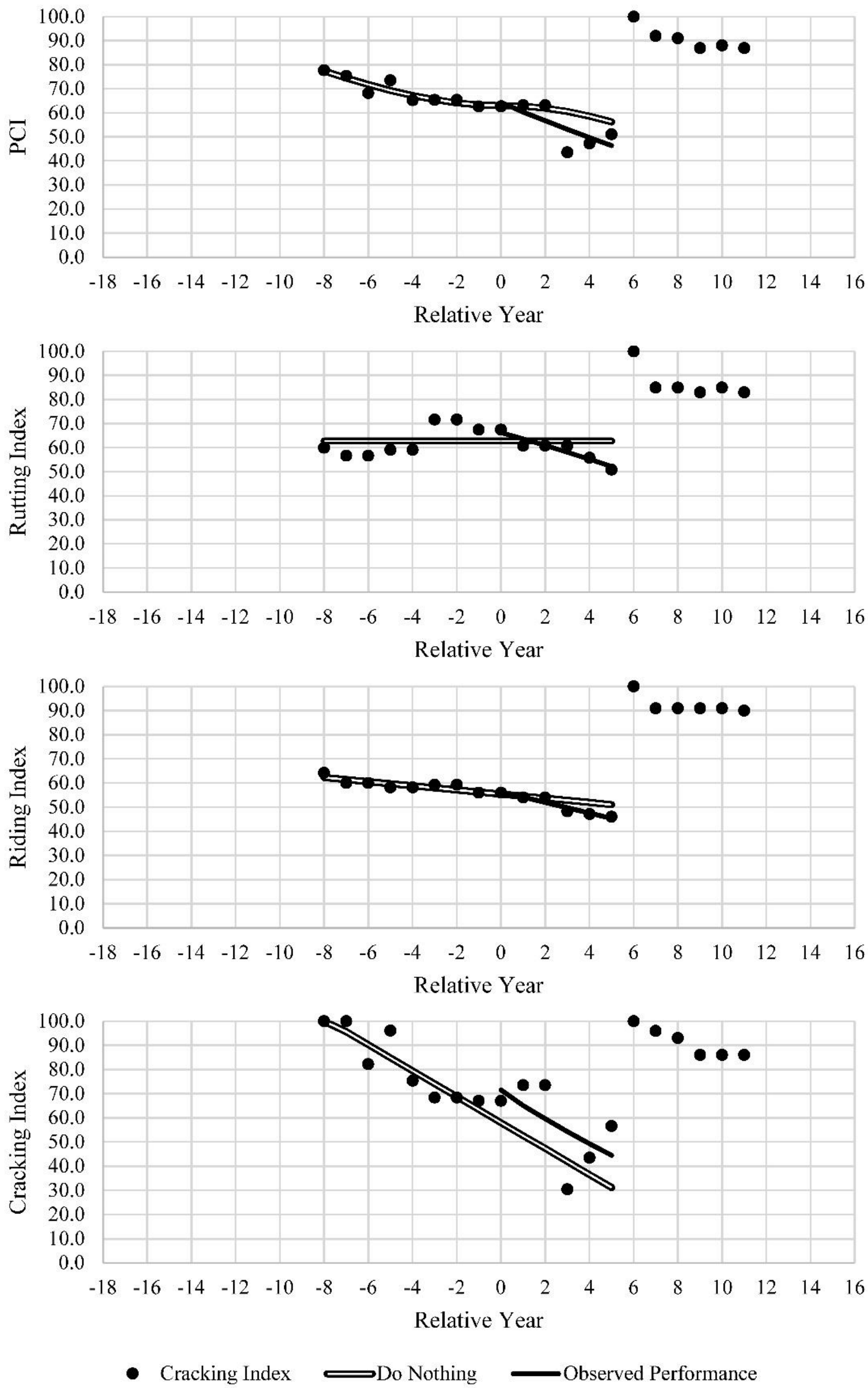


Figure 0-4 *Performance curves for MP-067-6(705)48--76-23*

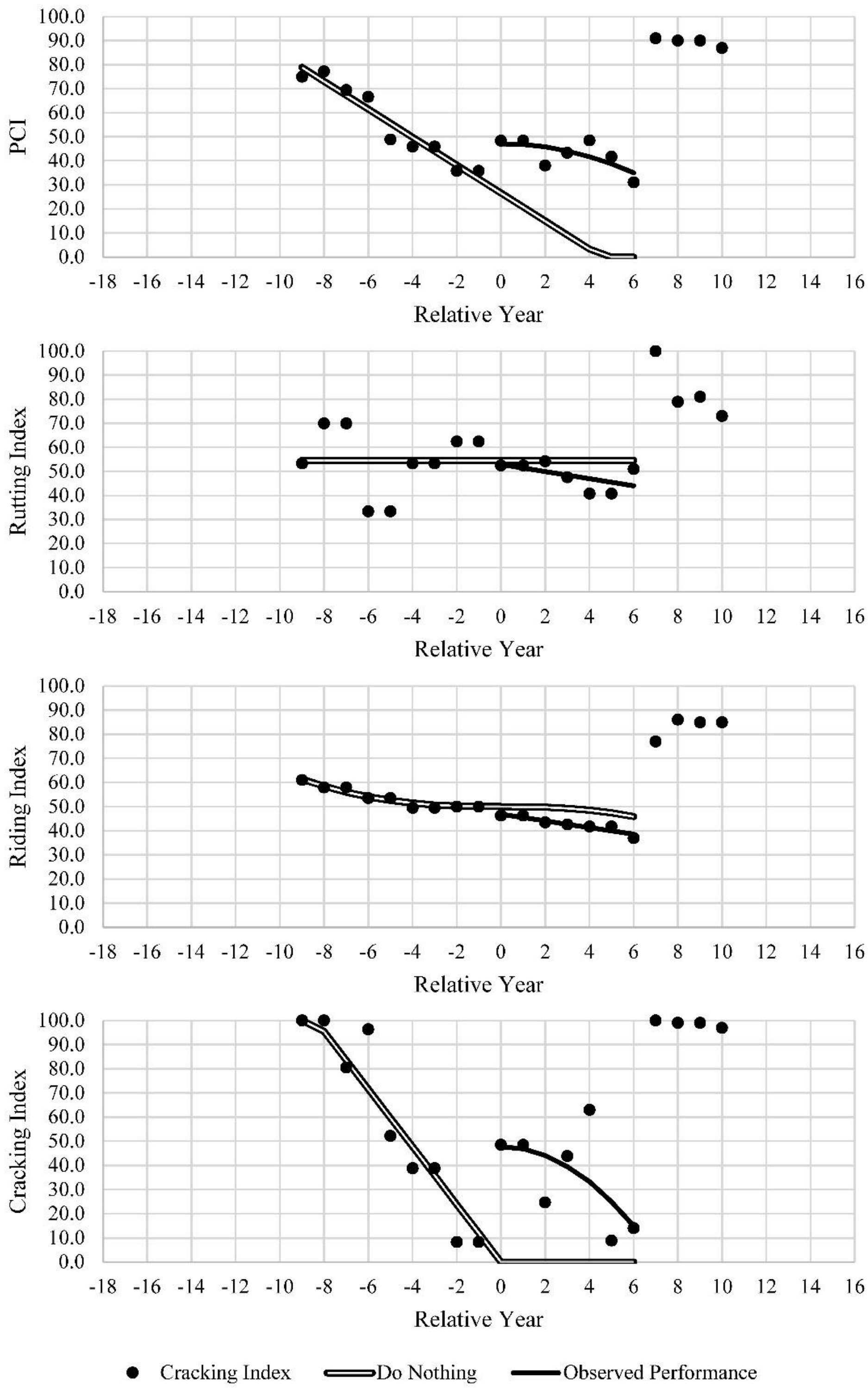


Figure 0-5 *Performance curves for MP-130-6(702)14--76-82*

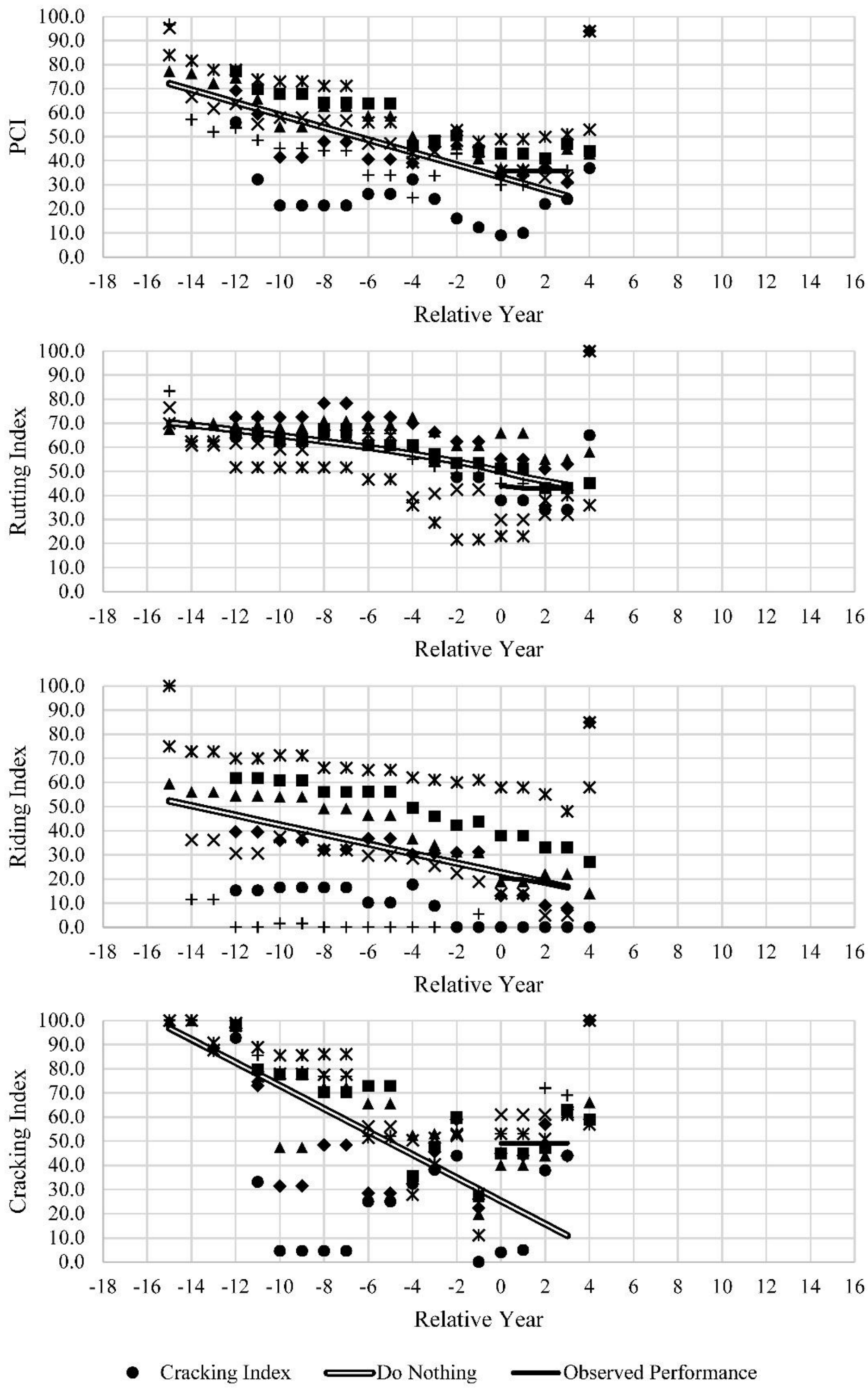


Figure 0-6 *Performance curves for MP-136-6(701)73--76-31*

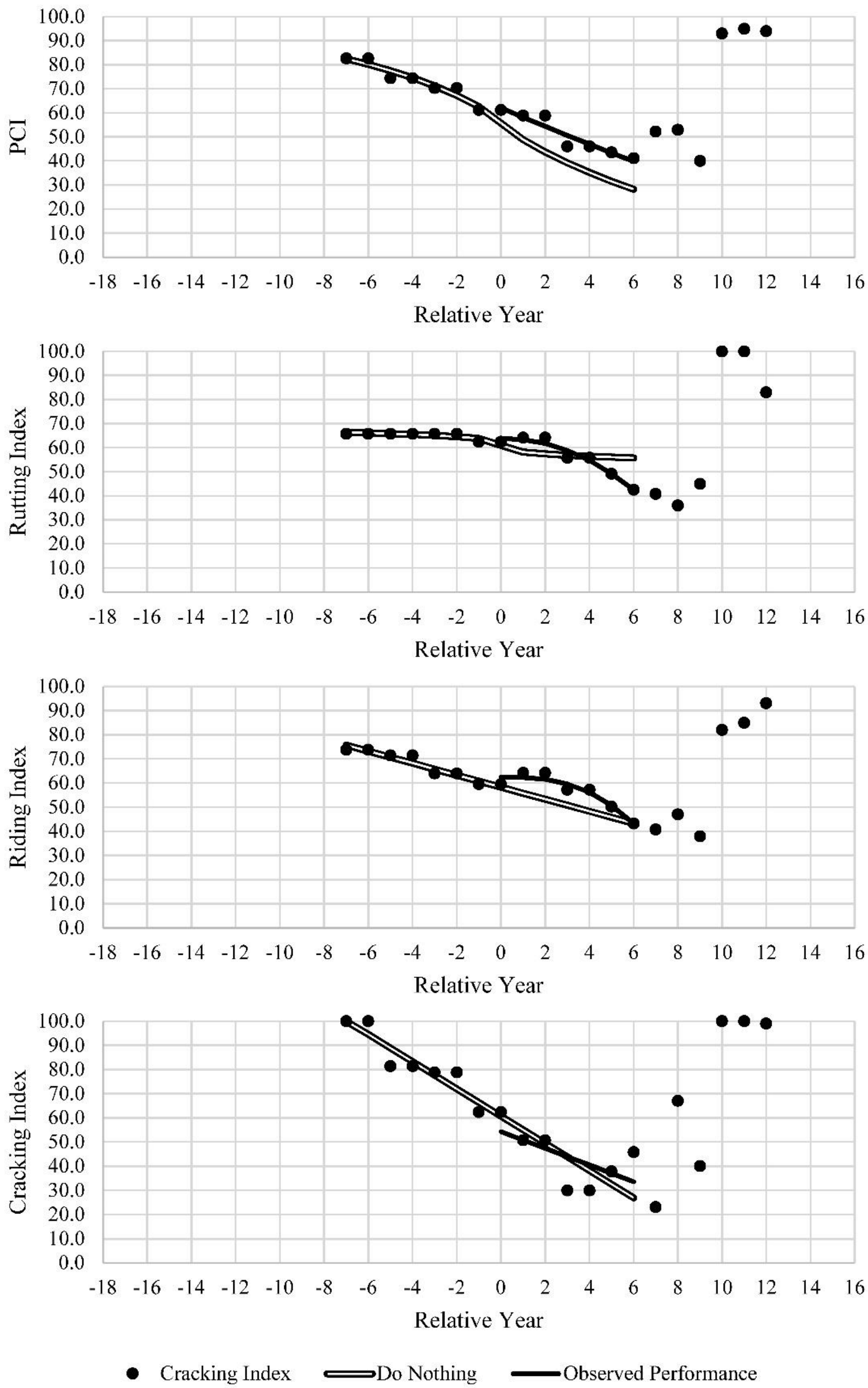


Figure 0-7 *Performance curves for MP-140-3(702)10--76-75*

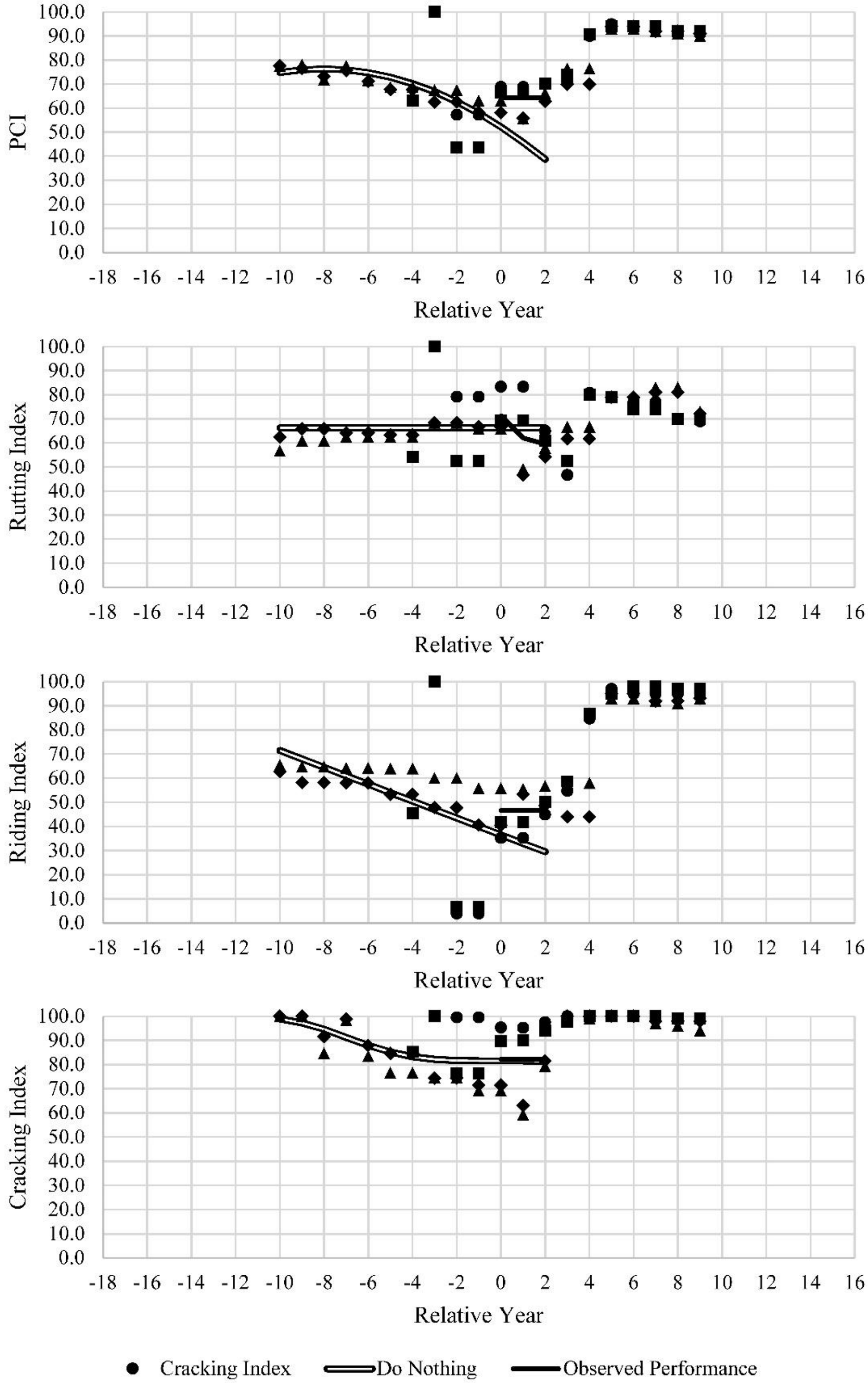


Figure 0-8 *Performance curves for MP-141-4(705)115--76-39*

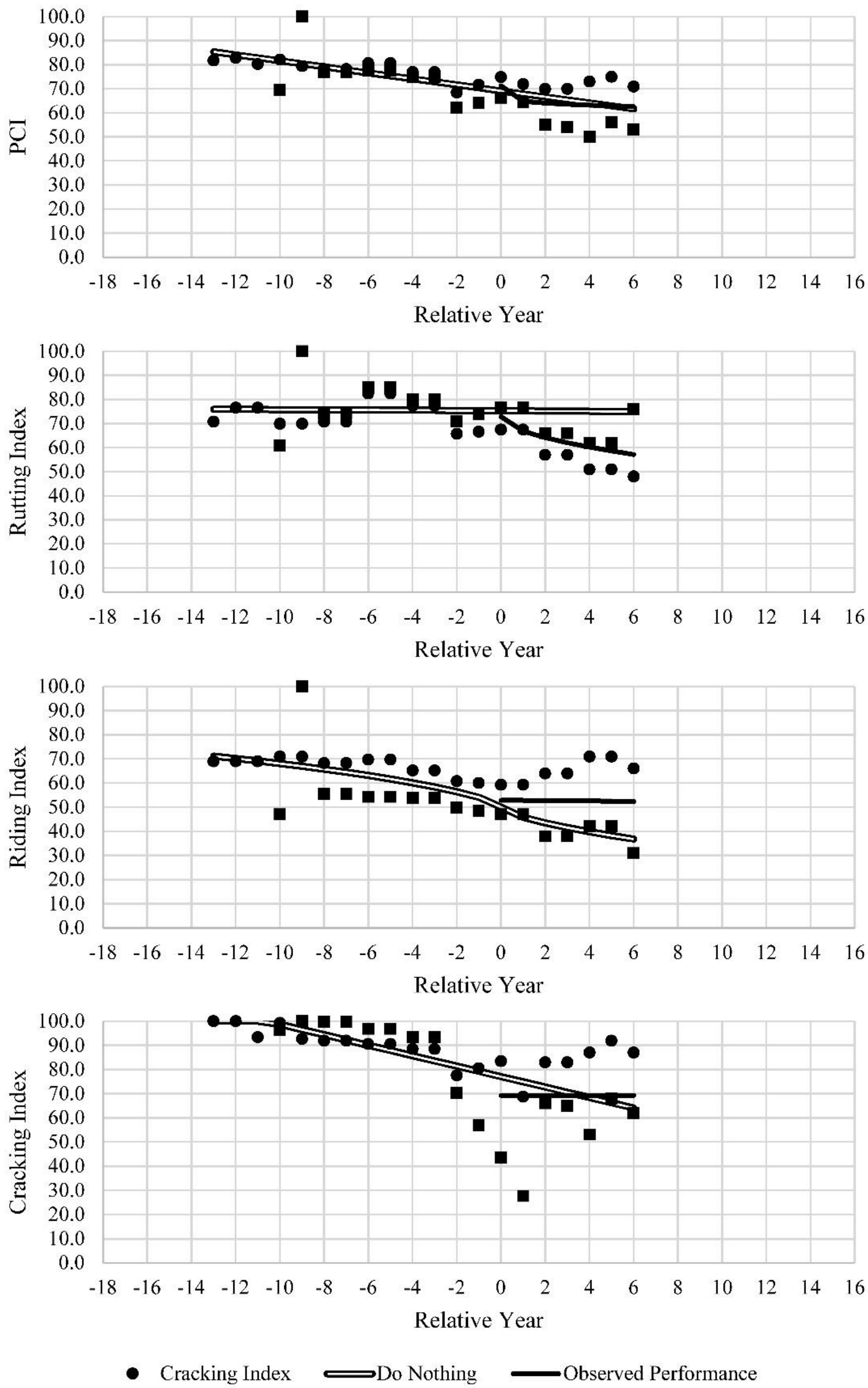


Figure 0-9 *Performance curves for MP-148-4(709)22--76-87*

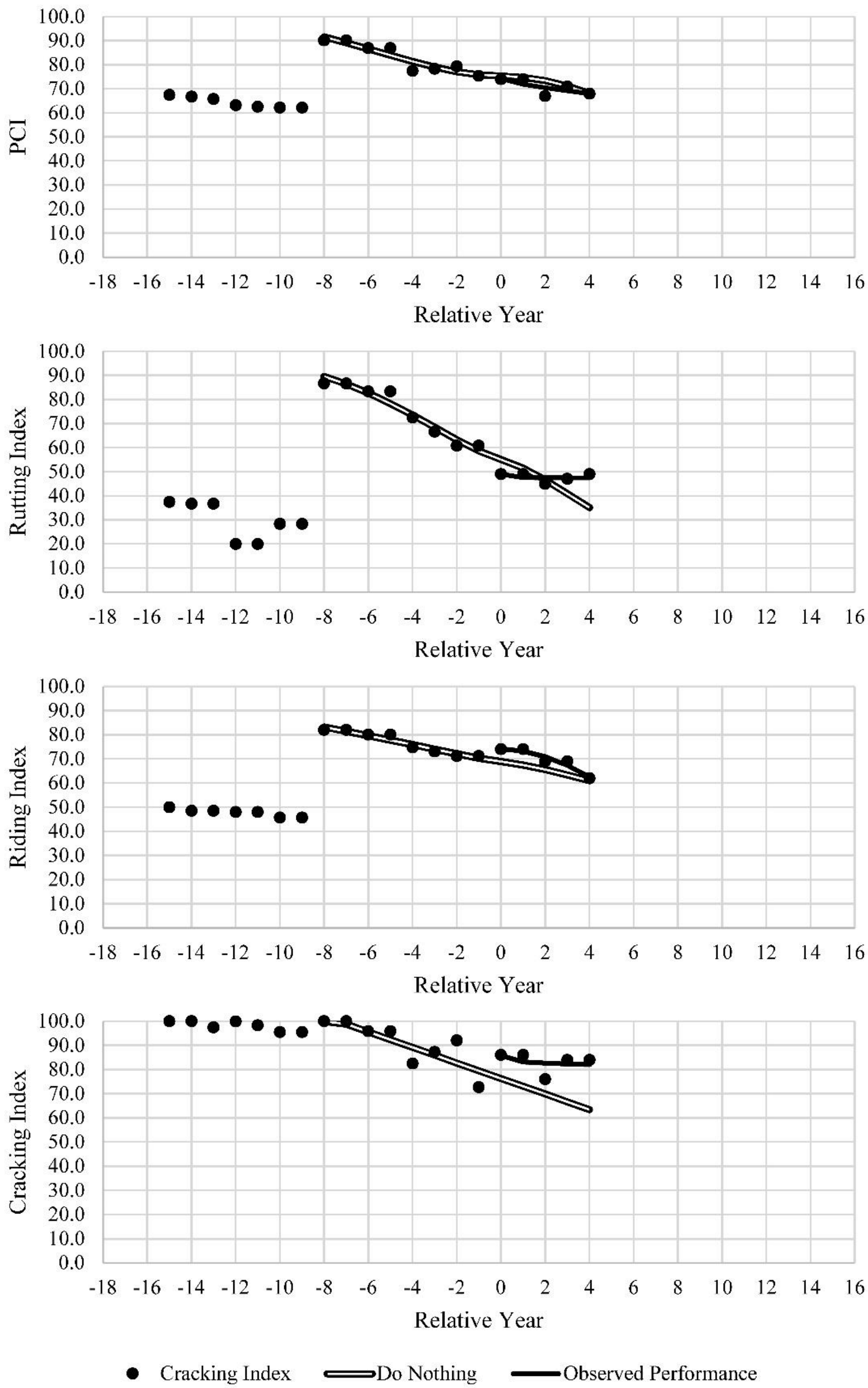


Figure 0-10 *Performance curves for MP-151-6(705)11--76-48*

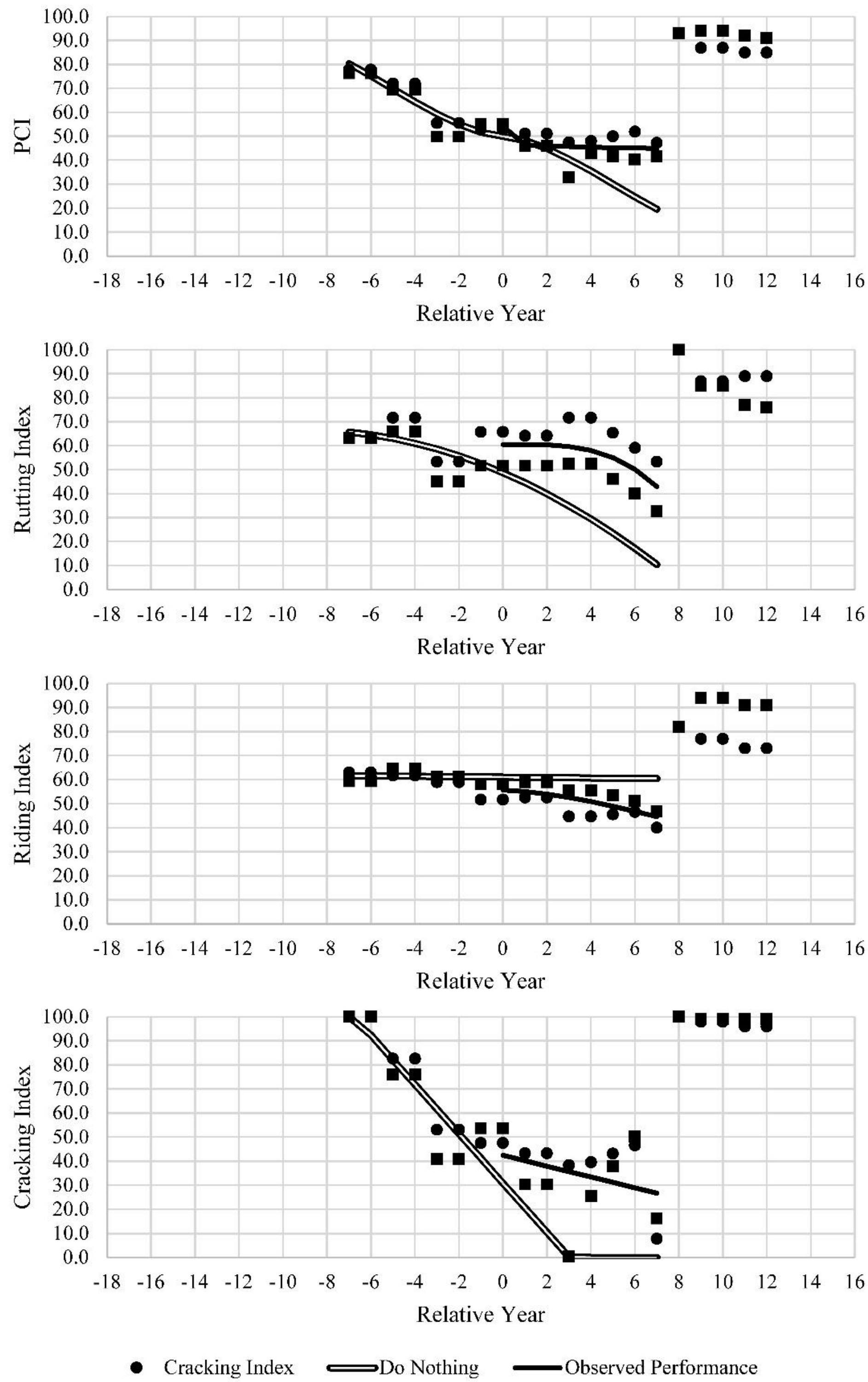


Figure 0-11 *Performance curves for MP-182-3(701)0--76-60*

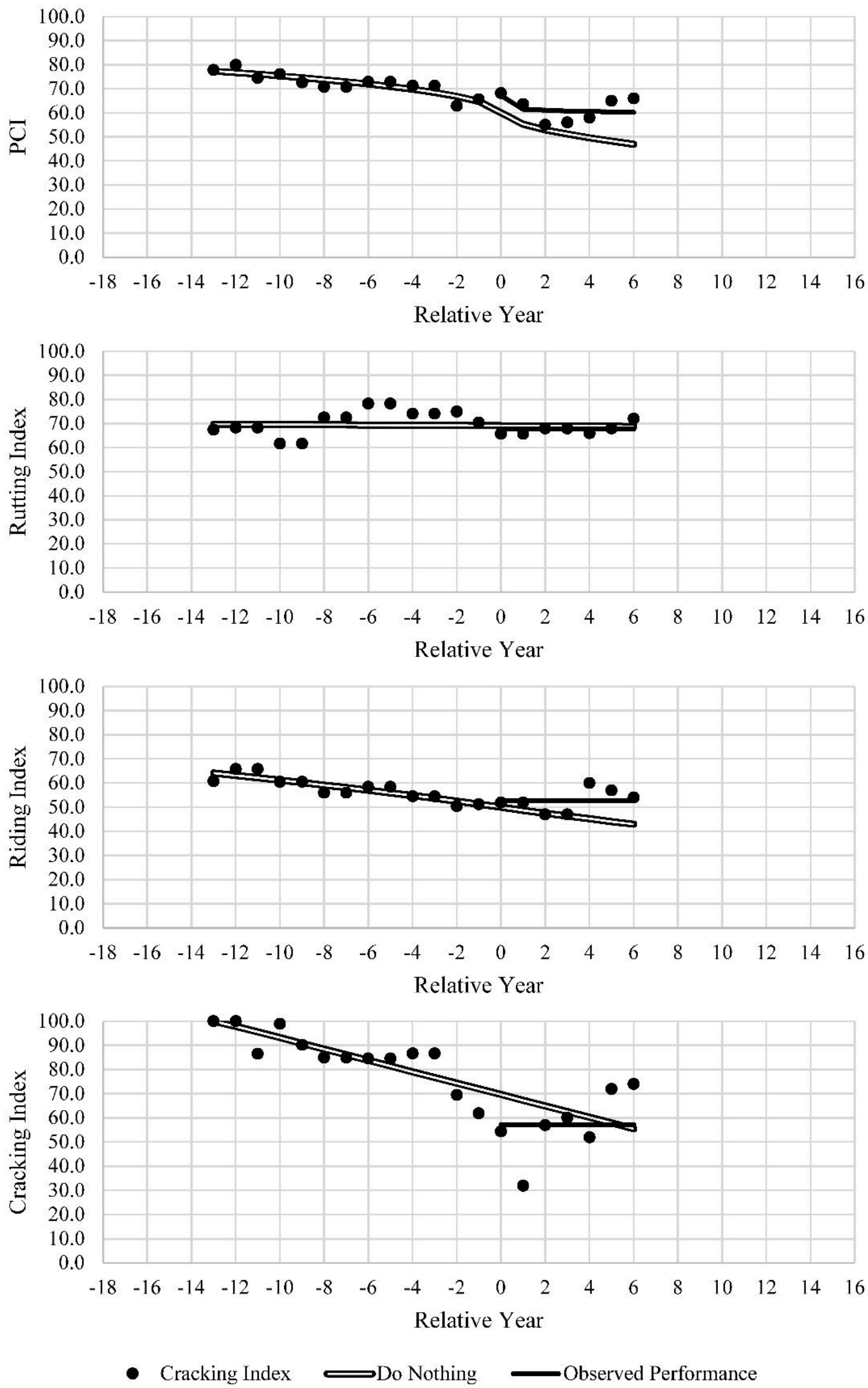


Figure 0-12 *Performance curves for MP-220-6(705)1--76-48*

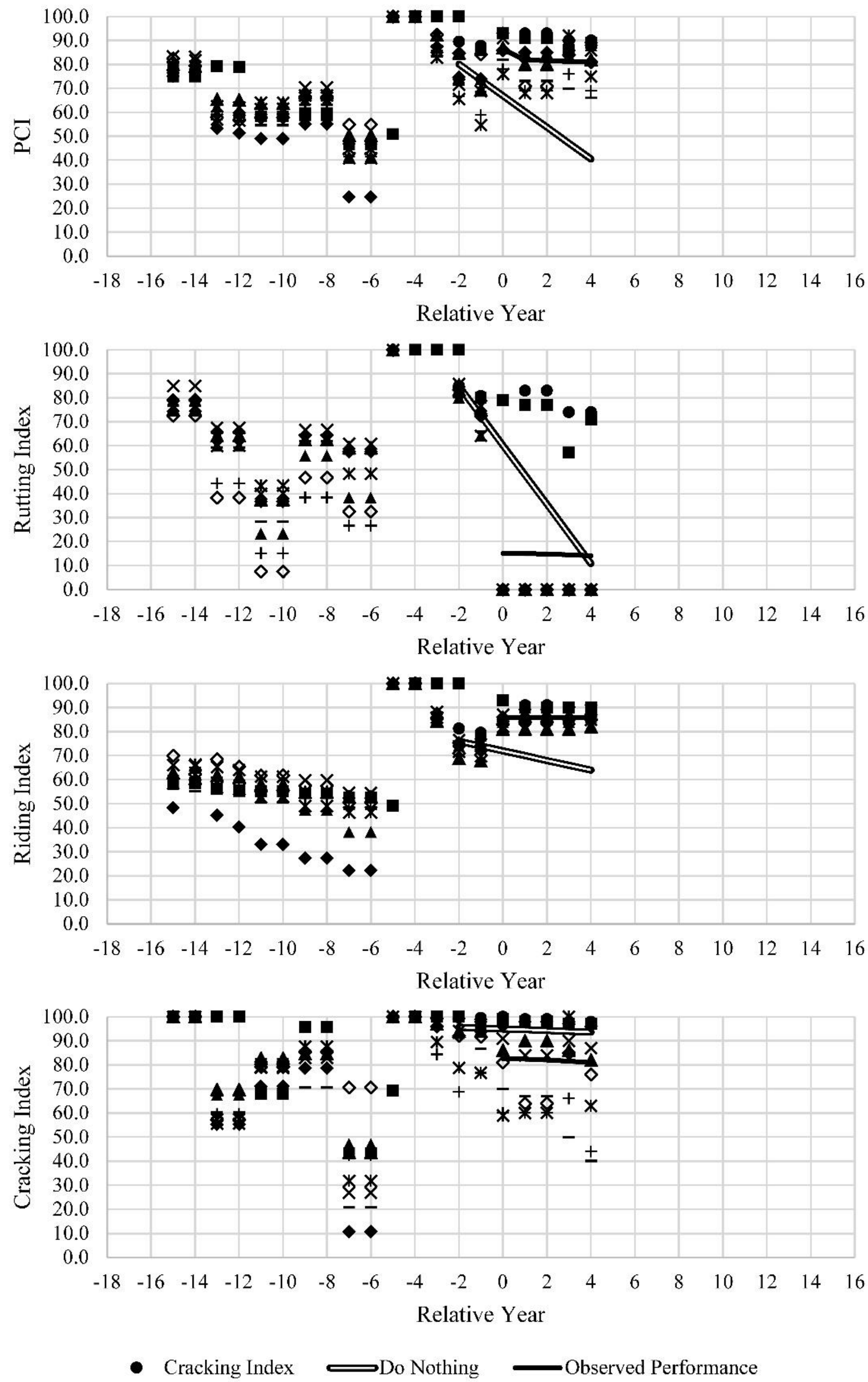


Figure 0-13 *Performance curves for MPIN-029-3(714)106--0N-67*