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Analytical methods to determine effectiveness of slurry seals in wet/freeze climate using pavement management information systems

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ABSTRACT
With increasing economic pressures worldwide, the amount of money spent on pavement preservation needs to become more effectively utilised. 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 analysed 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.

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PMIS; pavement preservation; slurry seals; pavement performance

Introduction and background

With increasing economic pressures worldwide, the amount of money spent on pavement preservation needs to become more effective and appropriately utilised. To properly allocate spending on pavement preservation, two general approaches utilising a pavement management system (PMS) can be used. The first approach involves prioritising various roads within a network, typically based on the roadway type (arterial, collector, residential, etc), current pavement condition, annual average daily traffic (AADT), and other factors important to the involved agency. However, the second approach involves the understanding of preservation performance based on actual treatments applied with local means and materials. Analysing past performance data and identifying trends provides the ability to better quantify the effectiveness of preservation treatments.

The objective of this study is to evaluate the performance of slurry sealing on Iowa roadways, a wet/freeze climate, to better understand their effectiveness as a pavement preservation treatment. Four pavement performance indices are evaluated and compared using reflected, logistic, sigmoidal (RLS) curves.

To provide context for this study, this background section reviews pavement management systems with a focus on Iowa's PMS efforts. Then, past studies focusing on the performance of slurry seals

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are presented followed by approaches for modeling pavement performance indices. Finally, studies examining the cost of preservation compared to rehabilitation are summarised.

PMS database

In a quote from the AASHTO (1993) 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 behaviour based on pre-existing trends seen across many projects, network-wide.

Possibly the most well-known PMS database is the Long-Term Pavement Performance (LTPP) 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). The LTPP program used generalised 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 categorisation (FHWA, 2003). Many research initiatives have already analysed the specific pavement study (SPS)-3 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. A study in Colorado used a network-level analysis to study the impact of maintenance and rehabilitation treatments on their low volume roadway network (Hafez et al., 2019). Studies such as these help to show the importance of collecting and maintaining state-wide pavement condition data to prioritise treatment strategies, especially for low volume roads. The City of Ottawa analysed their PMS pavement quality index (PQI) to evaluate the effectiveness of preservation, rehabilitation, and new construction using 20 years of project and performance data. When analysing their PQI, they found that ultra-thin overlays provided good values for their roadways (Ayed et al., 2018).

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 (a recently 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 and data is collected for every publicly owned road in the state. The PMIS data is collected for every 10 metres of roadway and includes detailed measurements of pavement distresses as well as traffic and pavement history. Performance data such as rutting and roughness are averaged for the 10 m section. Cracking data is reported as the length of cracks per 10 m section. Each cracking type is categorised by type of crack (transverse, longitudinal, fatigue/alligator) and by severity (Jeong et al., 2016). With such an extensive network of information (IaDOT, 2017), the data can have blemishes. 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 analysed. A study by Abdelaty et al. (2017) discusses that one of the major limitations for using PMS data for analysing project-by-project performance is data integration. This study focuses on project-level performance and has integrated performance data over time with the project location and project data. A broader goal for this study is to determine whether IaDOT's PMIS data can be used for reliable project-to-project performance analysis.

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.

A published study by Hajj et al. (2011) and a technical report by Souliman et al. (2012) analysed slurry seal performance in Nevada to find the ideal time to place a slurry seal over new construction. Results showed 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). On the other hand, 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). A study by Liu et al. (2010) found that modified slurry seal, or microsurfacing, initially reduced roughness but the data showed an abrupt return in roughness after a couple of years in service.

Modelling trends of pavement performance indices

A study by Yao investigated prediction models of asphalt pavement performance and found maintenance treatments are one the leading factors in overall performance of the asphalt roadway (Yao, Dong, Jiang, et al., 2019). Seen in a wide range of models, the function of PCI as a function of time has been interpreted differently by many researchers. Often, a curve depicting PCI as a function of time looks similar to 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 functionality of using a high-power polynomial for modelling is dependent on the quality and quantity of historical data. In situations where there is missing data or small data sets, a less sensitive model is useful. In these situations, a RLS curve can be used. A curve of this shape is often seen in cost benefit modelling of PCI over time (Galehouse et al., 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 generalised, 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 et al., 2015). Even further from the field of pavements, two United States Department of Agriculture researched developed the Van Genuchten-Gupta model, a modified sigmoid function, that was utilised 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 and Huang (2012), this approach was performed to analyse how overlay treatments impacted 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 and Huang (2012), then identify the area between these two trends as the observable benefit gained by performing the treatment. Index values are commonly used to analyse pavement performance. A study by Mousa et al. (2018) used a random cracking index to determine the cost effectiveness of crack sealing on 28 control/experimental sections. Yao, Dong, Ni, et al. (2019) used pavement condition index, ride quality index, and rutting depth index to show that using a combination of asphalt overlays and preventive treatments provided high cost-effectiveness.

Cost of preservation vs. rehabilitation

The primary difference between pavement preservation and pavement rehabilitation is the desired outcome. Pavement preservation can only be expected to reduce aging and restore serviceability, but pavement rehabilitation also needs to increase the pavement's strength (Geiger, 2005). Studies indicate that placing pavement preservation treatments earlier in a pavement's service life can lead to overall better performance of preservation treatments compared to waiting until later in the distress cycle (Buss et al., 2019; Peshkin & Hoerner, 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 analysing a curve, represented by an RLS function. Due to the initial plateau of the pavement performance curve, followed by a steep 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).

Materials and methods

In this research project, slurry seal projects constructed 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 (CL) sealing, longitudinal crack slurry sealing (LS), and transverse crack sealing (TL), also called transverse slurry levelling.

Slurry seal projects and projects locations

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. In this study, the slurry seals were used in the following ways: three projects sealed only the center-line, three projects sealed only longitudinal cracking, three 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 1. Although the number of projects is relatively few, the projects represent approximately 200 km of treated pavement. Project length, traffic, and general climate information is provided in Table 1. Climate data for each project was from LTPP Bind Online (FHWA, 2019).

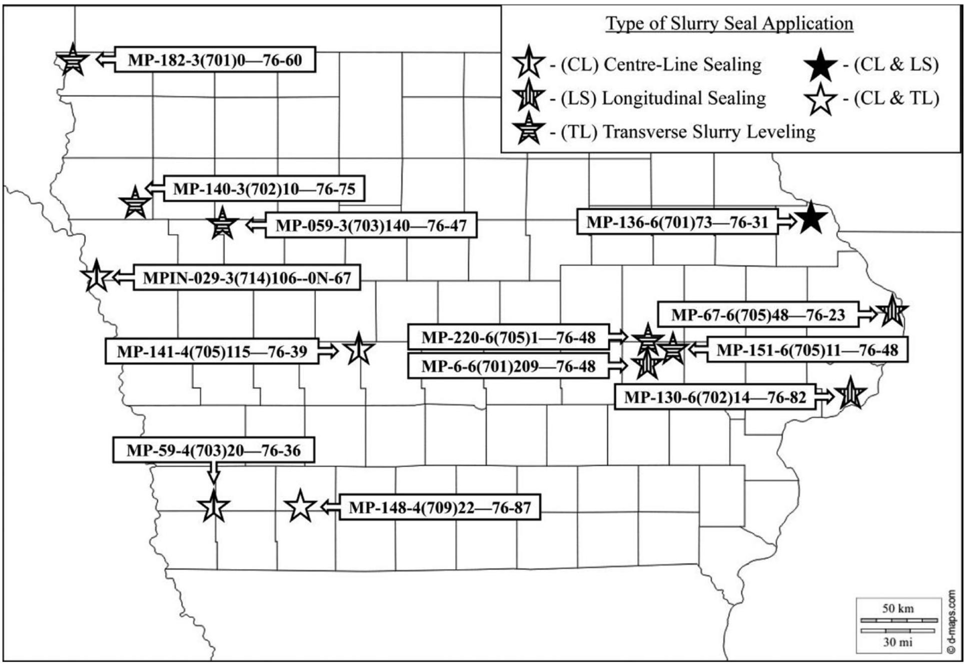

Figure 1. Location and type of slurry seal application of all eleven slurry seal projects located throughout the state of Iowa. (County map from https://d-maps.com/carte.php?num_car=7012&lang=en).

Table 1. Slurry seal project types, length, traffic and climate.

		Project data			
Slurry application	Project number	Project length in kilo-metres	AADT (% Trucks)	7-day ave. high air temp., °C	Lowest yearly air temp., °C
LS	MP-006-6(701)209–76-48	11.7	2425 (7%)	33.2	−41.7
TL	MP-059-3(703)140–76-47	22.7	2110 (18.2%)	33.91	−36.2
CL	MP-059-4(703)20–76-36	18.2	1350 (15%)	35.67	−33.7
LS	MP-067-6(705)48–76-23	11.3	1550 (7%)	32.91	−39.8
LS	MP-130-6(702)14–76-82	23.4	1350 (7%)	34.00	−39.00
CL/LS	MP-136-6(701)73–76-31	19.7	3,890 (14%)	33.88	−36.5
TL	MP-140-3(702)10–76-75	24.5	830 (17.1%)	34.67	−36.4
CL	MP-141-4(705)115–76-39	19.7	3890 (14%)	33.88	−36.5
CL/TL	MP-148-4(709)22–76-87	14.0	890 (not listed)	34.67	−33.1
TL	MP-151-6(705)11–76-48	6.8	6100 (7%)	33.2	−41.7
TL	MP-182-3(701)0–76-60	14.6	1760 (12.2%)	33.95	−37.8
TL	MP-220-6(705)1–76-48	8.6	3040 (4%)	33.2	−41.7
CL	MPIN-029-3(714)106–0N-67	55.0	14,200 (26%)	35.69	−32.3

Figure 2 is a picture illustrating various types of crack slurry sealing. Typically, the slurry treatment appears darker than the roadway but in this picture, the slag aggregate provides good contrast with the slurry that had been placed several years before this picture was taken. Transverse slurry sealing is placed on transverse cracks and helps to seal the crack and fill-in pavement depressions caused by the crack. Center-line cracking is slurry seal placed along the centre-line of the roadway and longitudinal slurry sealing is when the slurry is placed in a strip longitudinally along the roadway, typically in the wheel path (or wheel paths) where cracking is occruing.

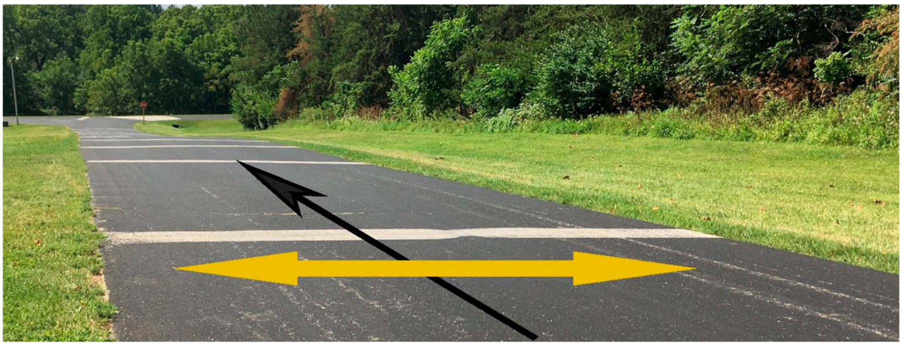

Figure 2. Example illustrating transverse slurry leveling (double-headed arrow) and black arrow illustrating centerline slurry sealing can also be placed in wheel paths or along centerline.

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.

Pavement condition index, rutting index, riding index, and cracking index 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. 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. Each index calculation 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. For these indices, 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.

The equation for calculating *PCI* is shown in equation (1) (Bektas et al., 2014).

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

The cracking index weighs the impact of various observed cracking, furthered explained in equation (2).

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

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, or fatigue, cracking index. The riding index is a scale that weighs the impact of the measured *IRI* values, where any values 0.5 m/km or lower result in an index value of a perfect 100 (Bektas et al., 2014). Lastly, the rutting index is zero for a pavement with 12.7 mm of rutting and the rutting index is 100 for a pavement with zero rutting and the index is scaled proportionally between 12.7 and 0.0 mm (Bektas et al., 2014).

Do nothing trends

Taking a modified approach to that of Dong and Huang (2012), the goal was to determine individual index benefits. The slurry seal study by Hajj et al. (2011) performs modelling with higher order

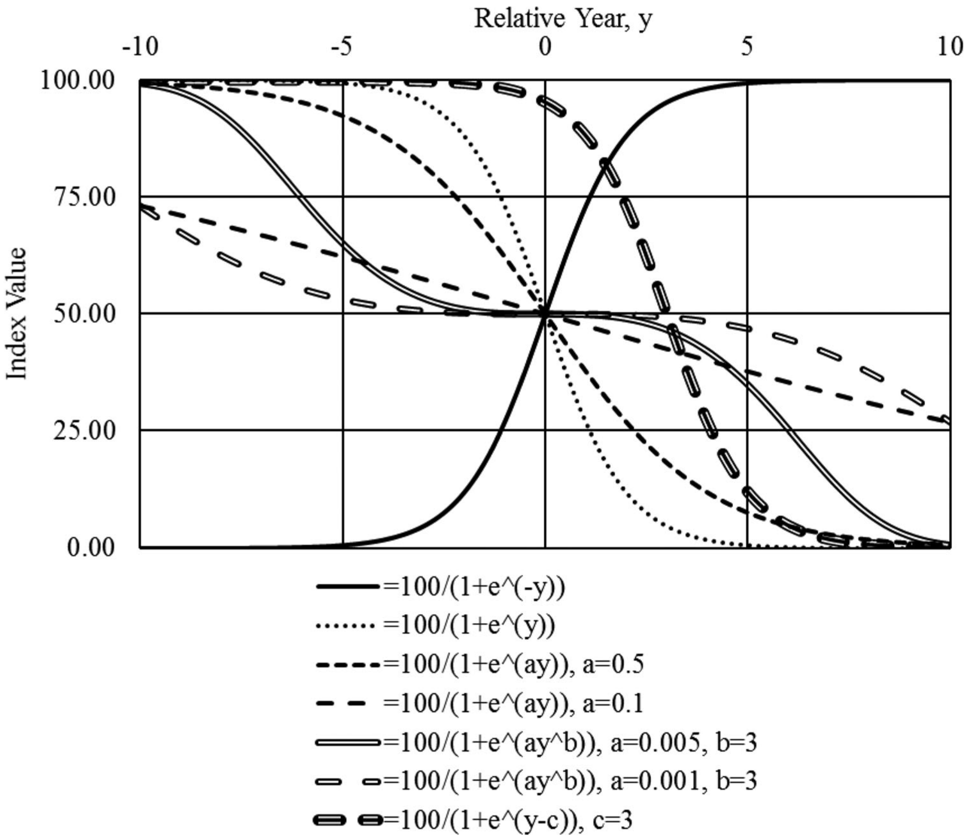

Figure 3. General graph of a sigmoidal curve and how the addition of coefficients can alter the original function.

polynomials but for this study, in order to provide a less sensitive model due to the small sets of preconstruction data, an RLS curve was chosen as the best approach.

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 observed 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 3 showcases how these changes take effect.

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).

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

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 minimising 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 equations (5) and (6), respectively.

$$\text{Linear Function} = -by + c \tag{5}$$

$$\text{Second-Order Polynomial} = -ay^2 - by + c \tag{6}$$

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

In an identical fashion to the 'Do Nothing Trends', the trend lines of the slurry seal performance were also fitted to individual RLS, second-order polynomial, or linear functions. The observed performance trends can be compared to the 'Do Nothing Trend', to determine the overall effectiveness for each slurry seal project.

Condition 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).

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

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 4 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.

Pavement 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

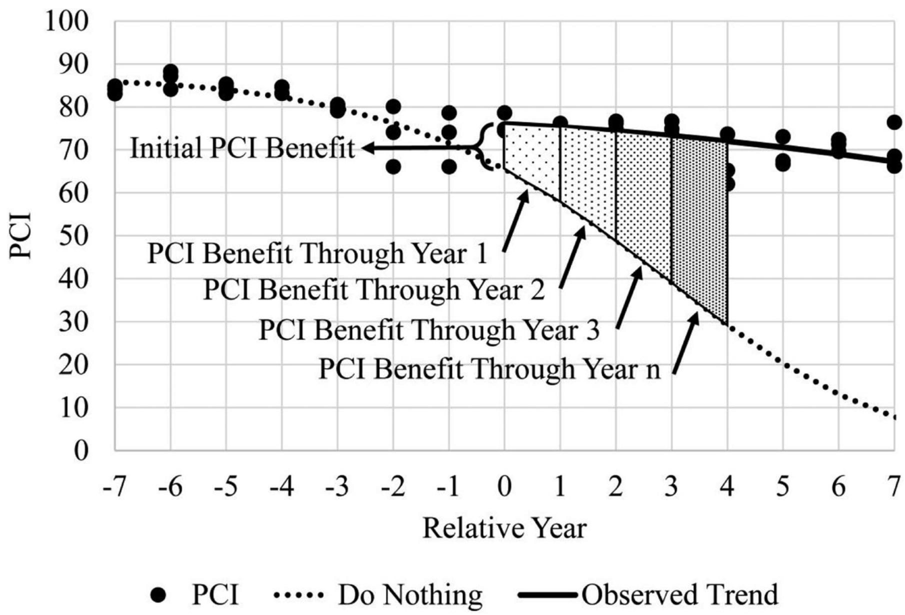

Figure 4. Index value benefits example.

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 analysing 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 indices benefits and service life extensions

'Do Nothing Trends' and 'Observed Performance Trends' will estimate actual service life extension for the other three individual indices similar to 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.

Results

All projects were analysed, and a best fit function was fitted to the data using an RLS 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 thirteen slurry seal projects. Each 'Do Nothing' and 'Observed Performance' trends for all four indices of all thirteen projects were measured and life extensions were evaluated. Statistical data from such small sample sets only provide limited results; however, observed trends over multiple projects help to develop performance expected trends as performance of more treatments becomes available.

Index benefits

To better explain the collected data, the index benefit throughout each relative year values 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 index benefits per 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.

The information in Table 2 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 5, 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 back to equation (1), although the cracking index benefits were substantial, only limited benefits for the ride quality and rutting indices were recognised 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.

The data was then broken into good, fair, or poor subset categories based on the predicted roadway condition at the time of treatment application. Figures 6–9 show the individual index value benefits for

Table 2. Quantity of projects with 'Do Nothing' and 'Observed Performance' trend data at each relative year from zero.

	Numberof projects with data						
Relative year	'Poor' PCI index	'Fair' PCI index	'Good' PCI index	Centre- 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

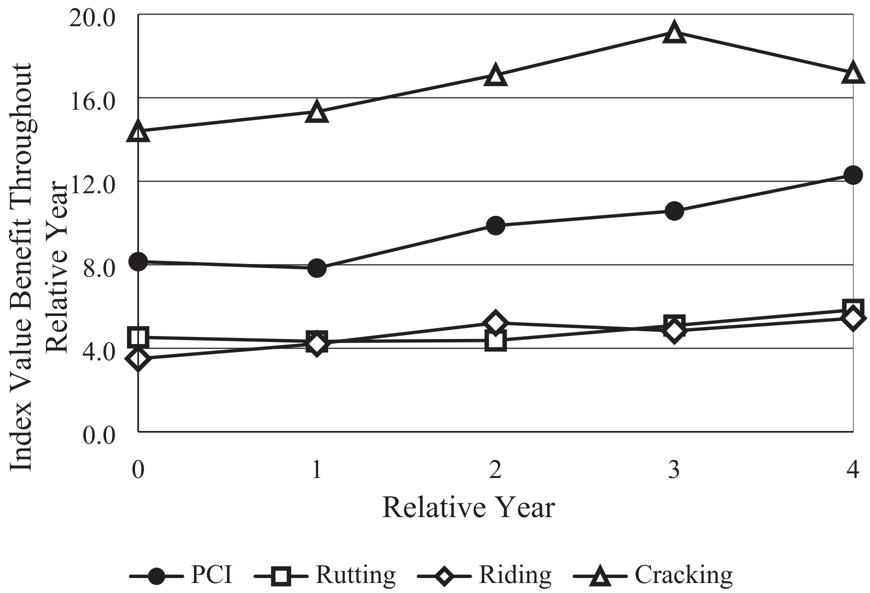

Figure 5. Index value benefits for all projects and all index value benefits averaged.

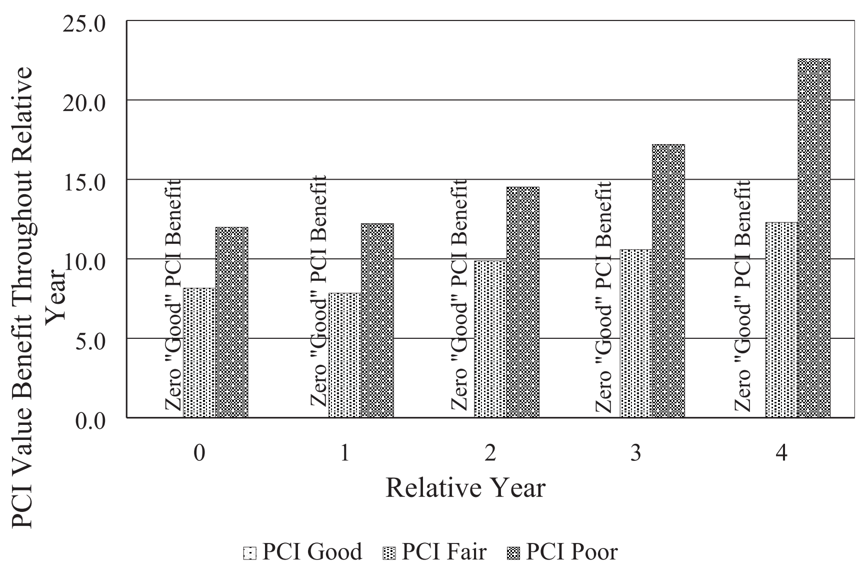

Figure 6. PCI value benefits analysed for projects categorised as good, fair, and poor. The 'good' category showed zero PCI benefit.

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 6 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

Figure 7. Rutting index value benefits analysed for projects categorised as good, fair, and poor. The 'good' category showed zero rutting index benefit.

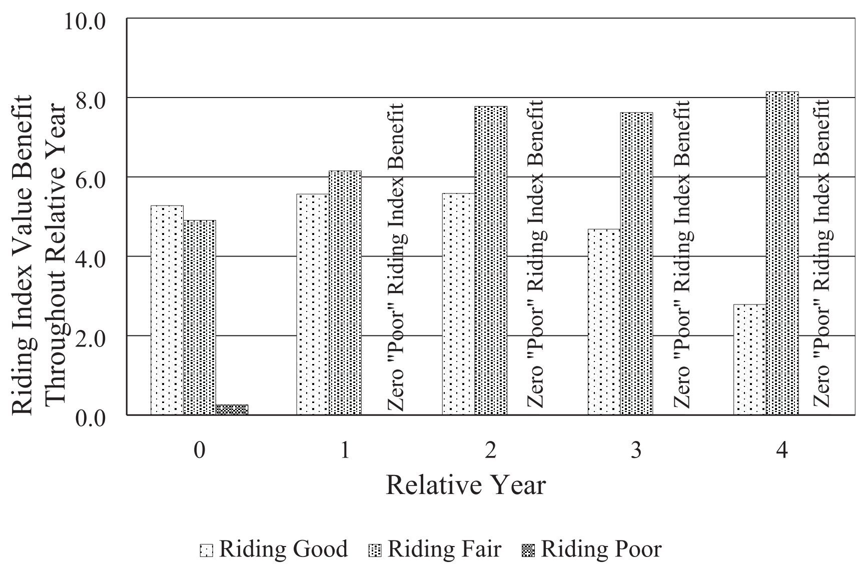

Figure 8. Riding index value benefits analysed for projects categorised as good, fair, and poor. The 'poor' category showed zero riding index benefit one year after placement.

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.

When examining the rutting index in Figure 7, 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 and 7.5 points, respectively. This shows that while the

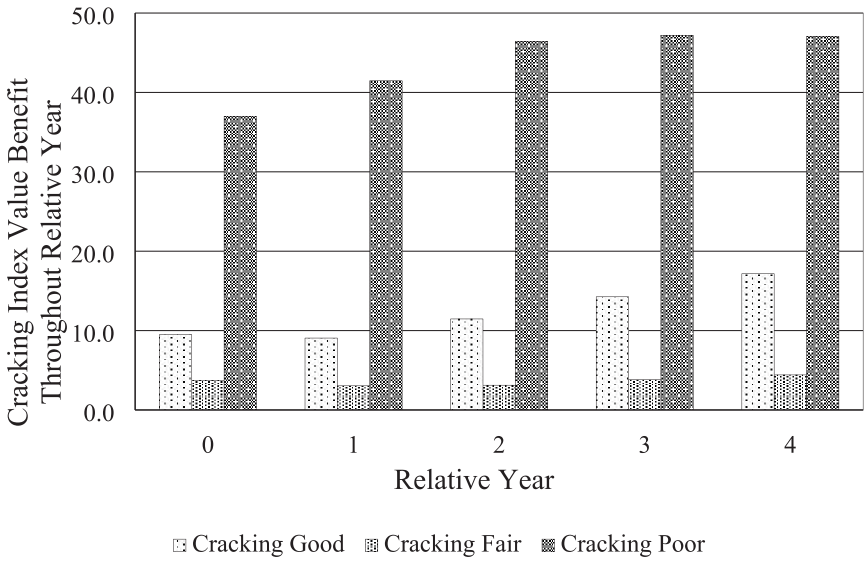

Figure 9. Cracking index value analysed for projects categorised as good, fair, and poor. All projects show some cracking index benefit after four years.

rate of deterioration of the pavement index remained very similar, the initial rutting benefit can be maintained for at least for years.

Unlike the PCI and rutting indices, the single 'Good' projects showed an improved benefit in the riding index. Figure 8 shows that an original benefit of 5–6 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 9 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 index benefits were analysed for each type of slurry seal application (approach 3), further trends were identified, as shown in Figures 10–12. For longitudinal crack sealing in Figure 10, 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.

When the center-line sealing was performed, Figure 11, 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 than the PCI and cracking index. The rutting index maintained a benefit of about 2–3 points from relative year zero to relative year three.

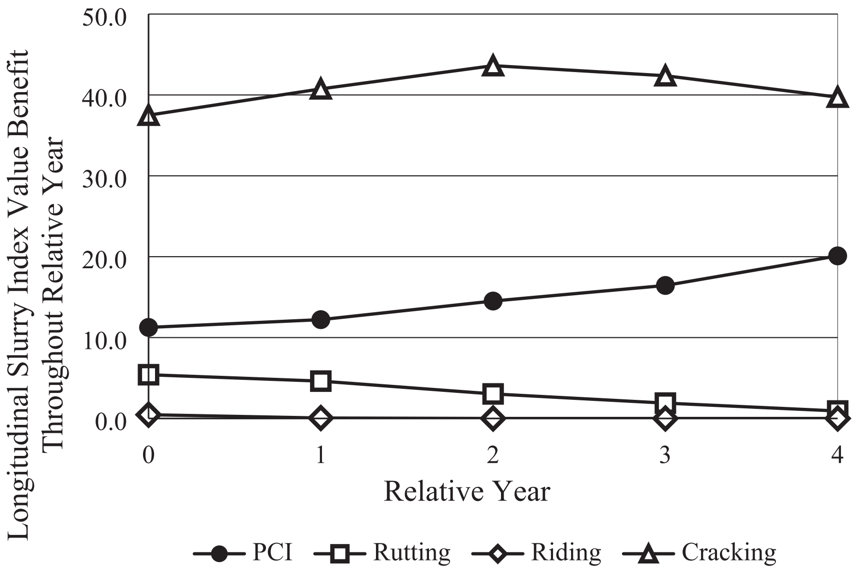

Figure 10. Index value benefits for longitudinal slurry sealing projects.

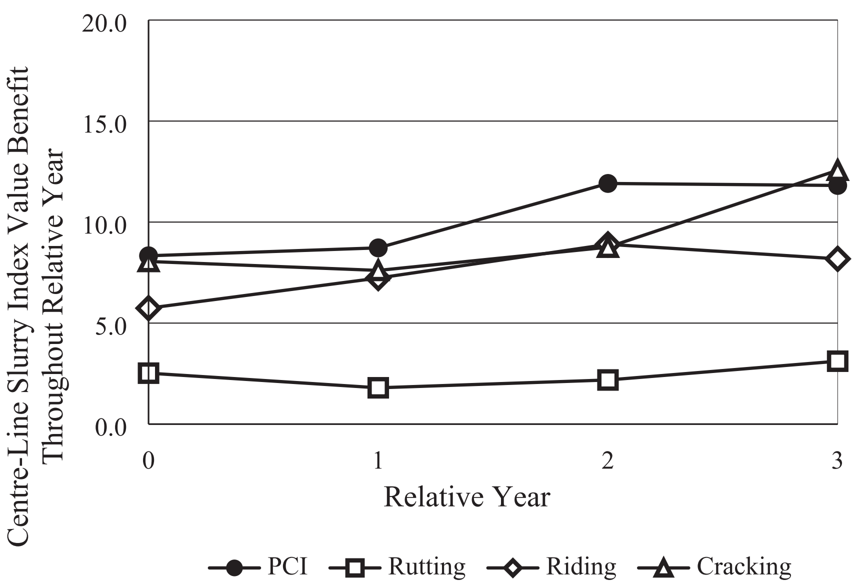

Figure 11. Index value benefits of centre-line slurry sealing projects.

After transverse levelling was performed, as seen in Figure 12, an initial benefit improvement of around 3–4 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.

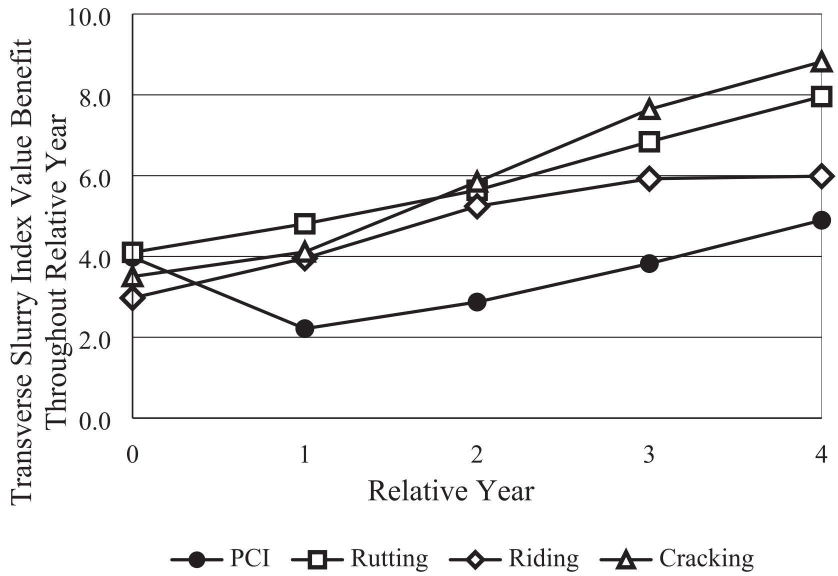

Figure 12. Index value benefits of transverse slurry leveling projects.

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. Figure 13 provides an example illustrating the analysis performed for each project to determine service life extension. The data points and performance curves are both shown. The performance curves represent an 'average' performance for the entire project and the 'average' may include several segments depending on the length of the project. The data points shown as squares and circles represent the index values for different segments along the project. The summary results for every project are displayed in Table 3.

To remain conservative, any service life extensions greater than 10 years were not included in respective service life extension averages. The values in Table 3 reflect a more conservative index service life extension because the large extensions are not factored in. The thirteen projects in total experienced an average PCI service life extension of 2.6 years. This value aligns with the two to four years and three to six years ranges observed in in other research studies. 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.

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 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.

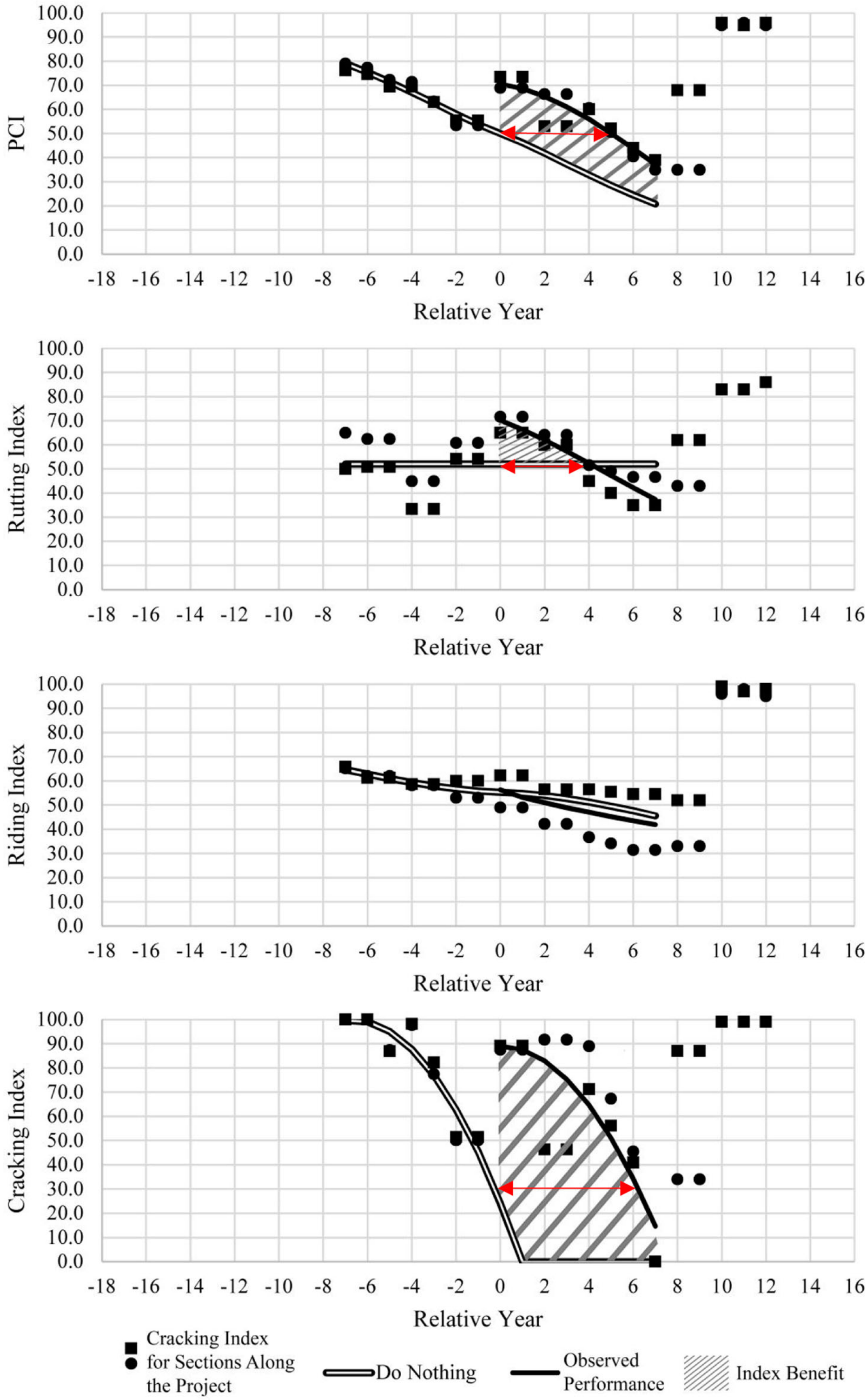

Figure 13. Example project analysis, MP-006-6(701)209–76-48, showing performance curves, index benefit, and arrows showing service life extension.

Table 3. Service life extension values for PCI, rutting, riding, and cracking indices.

			Index service life extension, years			
PCI category	Slurry application	Project number	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				
	Proj. 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.

While transverse slurry leveling 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. Centre-line slurry sealing is not expected to improve the riding index, but longitudinal slurry also showed minimal improvements to the riding index.

Conclusions

The following conclusions were made according to the data analysis:

In general, slurry sealing can improve the initial PCI of a pavement by 8.2 points and can extend the service life by 3.6 years. The rutting, riding, and cracking indices also showed initial improvements and displayed service life extensions no less than 2.2 years, limited by the riding index. In all 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, the initial improvements were seen across all indices, with the PCI service life expected to be around six years. The rutting and cracking indices show similar results, but slurry seals on these pavements still only improve the riding quality for about two years.

Pavements in 'poor' conditions (0 < PCI < 49.9) at relative year zero also show improvements to each index, but their expected PCI service life drops from around six years down to three years.

Longitudinal applications of slurry sealing, not including center-line slurry sealing, extend the expected service lives of each index by at least three years, expect for the riding index, where virtually no benefit or service life extensions are seen.

Center-line slurry applications show promising results with around one year of service life extension for the riding index and over five years of service life extension for PCI. The rutting index showed the least benefit over the first four years, but still can expect over two years of service life extension.

Transverse slurry sealing can be very effective in improving the riding index of a pavement. With the riding index experiencing around a seven-point jump in initial benefit, the service life of this index is five years. However, transverse sealing was shown to expect the shortest PCI service life extension, with a value of 2.7 years.

Almost always, 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 after slurry seal applications than before the treatment application. 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 project 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 and future decision-making frameworks. The goal of this study was to take aspects of other research and show analytical methods and models can be used to evaluate pavement performance based on data collected for a state-PMS database on a project-level.

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.

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References

AASHTO. (1993). *Design related project level pavement management, AASHTO guide for design of pavement structures (pp. 31–39)*. American Association of State Highway and Transportation Officials.

Abdelaty, A., Jeong, H. D., & Smadi, O. (2017). Barriers to implementing data-driven pavement treatment performance evaluation process. *Journal of Transportation Engineering, Part B: Pavements*, *144*(1), 04017022. https://doi.org/10.1061/JPEODX.0000023

Ayed, A., Halim, A. A. E., Viecili, G., Korczak, R., Ali, A., & O'Conner, S. (2018). Development of an approach for evaluating the pavement rehabilitation performance using City of Ottawa PMS data. In *TAC 2018: Innovation and technology: Evolving transportation-2018 conference and exhibition of the transportation association of Canada*.

Bektas, F., Smadi, O. G., & Al-Zoubi, M. (2014). Pavement management performance modeling: Evaluating the existing PCI equations. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1099&context=intrans_reports

Brown, E. R. (1988). *Preventative maintenance of asphalt concrete pavements, NCAT report 88-01* [Paper presentation]. Transportation Research Board 77th Annual Meeting, January 11–15, 1998, Washington, DC.

Buss, A., Claypool, B., & Bektas, F. (2019). *Effectiveness of pavement preservation technique*s. Institute for Transportation. https://intrans.iastate.edu/app/uploads/2019/06/effectvness_of_pvmt_preservation_techniques_w_cvr.pdf

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*(6), 6. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000378

Federal Highway Administration. (2009). *LTPP InfoPave: Tools. LTPPBind online*. US DOT Federal Highway Administration. Available at: https://infopave.fhwa.dot.gov/Tools/LTPPBindOnline

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

FHWA. (2009). *Long-term pavement performance program [Brochure]*. https://infopave.fhwa.dot.gov/InfoPave_Repository/Reports/A102020 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*(4), 767–783. https://doi.org/10.1080/14680629.2015.1057213

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]. https://www.fhwa.dot.gov/pavement/preservation/091205.cfm

Hafez, M., Ksaibati, K., & Atadero, R. (2019). Developing a methodology to evaluate the effectiveness of pavement treatments applied to low-volume paved roads. *International Journal of Pavement Engineering*, *20*(8), 894–904. https://doi.org/10.1080/10298436.2017.1356174

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*(1), 66–81. https://doi.org/10.3141/2235-08

Iowa DOT. (2017). Iowa DOT open data. http://data.iowadot.gov/datasets/pmis-2015

ISSA. (2010). *High performance slurry systems inspector's manual*. International Slurry Surfacing Association.

Jeong, H. D., Smadi, O., & Abdelaty, A. (2016). Historical performance evaluation of Iowa pavement treatments using data analytics. https://intrans.iastate.edu/app/uploads/2018/03/iowa_pvmt_tx_historical_perfomance_eval_using_data_analytics_w_cvr.pdf

Liu, L., Manepalli, V., Gedafa, D., & Hossain, M. (2010). *Cost effectiveness of Ultrathin bonded bituminous surface and modified slurry seal*. In Proceedings of the 1st International Conference on Pavement Preservation, April 12–16, 2010, Newport Beach, California.

Mousa, M., Elseifi, M. A., Bashar, M., Zhang, Z., & Gaspard, K. (2018). Field evaluation and cost effectiveness of crack sealing in flexible and composite pavements. *Transportation Research Record*, *2672*(12), 51–61. https://doi.org/10.1177/0361198118767417

Peshkin, D. G., & Hoerner, T. E. (2005). *Pavement preservation: Practices, research plans, and initiatives*. American Association of State Highway and Transportation Officials.

Souliman, M. I., Hajj, E. Y., & Sebaaly, P. E. (2012). Effectiveness of single and sequential applications of slurry seals on asphalt pavements in the Truckee meadows region.

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*, 730–737. https://www.ars.usda.gov/arsuserfiles/20361500/pdf_pubs/P1295.pdf

Yao, L., Dong, Q., Jiang, J., & Ni, F. (2019). Establishment of prediction models of asphalt pavement performance based on a novel data calibration method and neural network. *Transportation Research Record*, *2673*(1), 66–82. https://doi.org/10.1177/0361198118822501

Yao, L., Dong, Q., Ni, F., Jiang, J., Lu, X., & Du, Y. (2019). Effectiveness and cost-effectiveness evaluation of pavement treatments using life-cycle cost analysis. *Journal of Transportation Engineering, Part B: Pavements*, *145*(2), 04019006. https://doi.org/10.1061/JPEODX.0000106