ANALYSIS OF EFFECTIVENESS OF PAVEMENT PRESERVATION USING LONG-TERM PAVEMENT PERFORMANCE DATA

By

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ABSTRACT OF THE THESIS

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Pavement preservation can retard the development of pavement distresses and improve pavement functional performance. Quantification of the effectiveness of preservation has important implications for the selection of pavement maintenance strategies and decision making in pavement management system. Most of previous studies mainly focused on the effectiveness of preservation on pavement serviceability index (PCI) and roughness; few studies considered the effectiveness of preservation on individual pavement distresses and pavement surface friction. The objective of this thesis is to investigate the effectiveness of pavement preservation on mitigating multiple pavement distresses and restoring pavement surface friction.

The datasets are selected from the Specific Pavement Studis-3 (SPS) experiments of the Long Term Pavement Performance (LTPP) program. The SPS-3 includes the performance of four preservation treatments (thin overlay, chip seal, crack seal, and slurry seal) under five design factors (traffic, temperature, precipitation, existing pavement condition, and subgrade type).

The pavement distresses considered in the analysis include fatigue cracking, longitudinal cracking, transverse cracking, and rutting. The effectiveness of pavement preservation is quantified using the distress area ratio, which is associated with the areas under the distress curves after treatments and the distress curves with do-nothing. Statistical tests were used to compare the effectiveness of preservation treatments and identify the significant factors that affect the effectiveness of preservation. Results show that chip seals have little effectiveness in rutting prevention; slurry seals demonstrate effectiveness in longitudinal cracking; crack seals show effectiveness in fatigue cracking.

On the other hand, the effectiveness of preservation treatments on pavement surface friction and the long-term variation of friction were investigated. The results of statistical analysis indicate that slurry seal causes significantly greater friction number compared to the control section. Stepwise regression analysis was conducted to quantify the influence of various factors on the long-term variation of pavement friction. The precipitation, freeze index, and pavement roughness showed significant correlation to the friction number in the regression models.

The analysis results can aid state pavement agencies better select the appropriate maintenance treatments based on the existing pavement condition to maximize the effectiveness of preservation treatment.

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Chapter 1 Introduction

1.1 Background

Since the early 1990s, the massive construction of the interstate highway system has declined. The Federal Highway Administration (FHWA) started to increase focus on pavement preservation (preventive maintenance) and address the deterioration of the nation's highway. It is reported by the FHWA that the cost to maintain the pavement in the National Highway System at existing condition levels is about $50 billion per year [1]. The implementation of pavement preservation is demonstrated in Figure 1. Studies have shown that every $1 spending on pavement preservation treatment in the early stage is equal to spending $6 to $10 on future rehabilitation or reconstruction costs [2]. Thus pavement preservation is an economical maintenance alternative for highway agency.

Compared to rehabilitation, preventive maintenance treatments mainly focus on surface refreshment to alleviate functional deterioration of pavement, such as friction, minor cracking, or oxidation of the asphalt pavement, rather than structural deterioration. Preventive maintenance can be used to prevent minor deterioration, retard pavement failures, and reduce the chance for corrective maintenance or rehabilitation and thus prolong the pavement service life.

Figure 1 Timing of Pavement Preservation [3]

Typical preventive treatments include thin overlay, chip seal, slurry seal, crack seal, microsurfacing, fog seal, sand seal, cape seal, and etc. These treatments have different construction processes and costs. A number of studies have been conducted to compare the performance of various pavement preservation treatments using the Long-Term Pavement Performance (LTPP) database or the pavement management database maintained by state Department of Transportation (DOTs). The LTPP program is a 20-year study of in-service pavements in the U.S. and Canada. The main goal of LTPP is to extend the service life of pavements through various designs of pavement structures by implementing different materials or under different factors such as precipitation, traffic, temperature, subgrade soil, or maintenance practices. The Special Pavement Studies-3 (SPS-3) experiment in the LTPP program was designed in 1990 to evaluate the effectiveness of preservation options and to decide the cost-effective methods for applying preservation treatments for flexible pavements

[4]. It provides large amounts of data that can be utilized to analyze the effectiveness of preservation on pavement performance.

Quantification of the effectiveness of preservation has important implications for the selection of pavement maintenance strategies and decision making in pavement management system. Without knowing the effectiveness of different treatments, it is difficult to determine which type of preservation treatment should be implemented based on the severity and type of pavement distress. Construction, design, structure, material, environment and traffic, which play important roles in the pavement deterioration process, also influence the effectiveness of preservation treatments. Specific treatment method and pre-treatment pavement condition are another two important factors for the performance of preservation. The highway agencies are interested in selecting appropriate preservation treatments based on the specific local conditions.

Pavement surface friction is an important safety issue related to pavement surface condition. Adequate friction (skid resistance) generated at the tire-pavement interface is a significant contributing factor to mitigate the risk of road accidents and improve public safety. Higher pavement friction can decrease vehicle braking distance and prevent vehicle-related crashes. However, pavement friction performance deteriorates with time under repeated traffic loading and due to environmental effect. The evolution of pavement surface friction varies with age, traffic, temperature, distress, wet/snow/ice condition, and contamination, among other factors [5]. Therefore, it is important to evaluate the effectiveness of preservation treatment on pavement friction and its long-term degradation process. This would help developing effective pavement maintenance practices in providing good skid resistance over the total pavement service life for highway safety management.

1.2 Problem Statement

When the pavement reaches the stage of preventive maintenance, there are a variety of treatments available. The overall effectiveness of the treatments has been studied by many researchers and the selection guidelines of preventive treatments have been established by some state DOTs. However, when selecting the preventive treatment according to the existing pavement condition with different types of distresses, a lot of factors should be considered. The state DOTs' guidelines usually provide the general and ambiguous treatment recommendations under many circumstances.

There are two types of pavement performance: performance in terms of structural integrity and performance in terms of safety and drivability. The former is related to distresses such as rutting and cracking; the latter is related to surface friction and smoothness. Effectiveness is defined as the quantitative influence on the pavement condition resulting from the application of a preventive maintenance treatment. Using this definition, different levels of effectiveness may be obtained for a specific preventive maintenance treatment depending on the target pavement distress.

A number of previous studies have used the LTPP database and investigated the effectiveness of preservation on pavement condition index (PCI) or international roughness index (IRI). Although the IRI or PCI has been widely used as an indicator to represent pavement performance, it is difficult to recommend preservation treatments that are matched to individual pavement distresses because IRI or PCI represents the contributions of various pavement distresses and defects. Further studies are still needed to investigate the performance of preservation with respect to the specific pavement surface distress (such as fatigue cracking, top-down cracking, and low-temperature cracking). In addition, the influence of design factors on the effectiveness of pavement preservation has not been thoroughly studied.

1.3 Objective and Scope

The objective of this study is to investigate the effectiveness of pavement preservation on mitigating multiple pavement distresses and restoring pavement surface friction at different climate, traffic and existing pavement conditions. It is anticipated that such information can assist highway agencies in choosing the appropriate preservation treatment.

In order to achieve this objective, the following research tasks are conducted:

1. Evaluate the effectiveness of four pavement preservation treatments (chip seal, slurry seal, crack seal, and thin overlay) on mitigating multiple pavement distresses.
2. Evaluate the effectiveness of four preservation treatments on pavement surface friction and its long-term variation.
3. Identify the effect of climate, traffic, existing pavement condition, and subgrade type on the effectiveness of pavement preservation.

This thesis is divided into five chapters. The first chapter introduces the background, problem statement, and objective. The second chapter summarizes previous research on the effectiveness of pavement preservation and the selection guidelines used by state DOTs. The third chapter analyzes the effectiveness of preventive treatments in preventing fatigue cracking, longitudinal cracking, transverse cracking and rutting. The fourth chapter analyzes the effectiveness of preventive treatments on the skid resistance of pavement. The final chapter presents analysis findings, conclusions, and future study recommendations.

Chapter 2 Literature Review

2.1 Types of Preservation Treatment

Preventive maintenance or preservation is a cost-effective activity applied at relative early stage of pavement service life. Table 1 presents the basic performance of several preventive treatment ordered in the cost [6, 7, 8, 9, 10, 11]. Those treatments can improve pavement functional performance, retard certain distress development and reduce deteriorate rate.

2.2 Previous Findings on Effectiveness of Pavement Preservation

This section summarizes the previous findings on the effectiveness of preventive treatments with a focus on four treatments: crack seals, slurry seals, chip seals, and thin overlay. These findings are organized respectively for each type of treatment.

Thin Overlay

Studies from LTPP database proved the outstanding performance of thin overlay. A FHWA sponsored study in 1998 investigated the LTPP SPS-3 test sections based on surveys from Expert Task Groups (ETG) and analyzed the data from the LTPP database. The results concluded that the best performance with respect to cracking was found in the thin overlay and chip seal sections [2]. A comprehensive NCHRP study was conducted in 2000 to analyze the data from all the LTPP SPS-3 sites [12]. The study found that the thin overlay was the only one to demonstrate a significant initial effect on rutting.

Table 1 Summary of Major Preventive Treatments

Preventive Treatment	Description	Characteristic	Typical Life Extension	Cost (1000$/ per lane mile)
Crack Seals	Crack preparation followed by the placement of a high-quality asphalt material	Prevent the intrusion of water	1-2	1.5-2.5
Fog Seals	A light spray (typically 0.05 to 0.15 gal/yd^2) of a diluted asphalt or rejuvenator emulsion	Delay further oxidation, weathering and raveling, provide edge-shoulder delineation	1-2	2.4-3
Sand Seals	Emulsion asphalt with broom scrubbing followed by application of small aggregate with second brooming, thicknesses range from 6mm to 10mm	Fill air voids, surface narrow cracks, rejuvenate the oxidized asphalt and poor friction	3-4	5-8
Flush Seals	Application of sprayed film of emulsion bituminous binder followed by light covering of fine aggregate	Seal pavement surface and prevent infiltration of water	2-5	6-15
Slurry Seals	Mixture of emulsion asphalt and well-graded aggregate with surface thicknesses of 10 to 20mm	Provide skid resistance, perform best in warm-weather climates	3-6	7-11.5
Chip Seals	Sprayed with asphalt and then immediately covered with aggregate and rolled	Seal small cracks, wearing course on low-volume roads	4-6	7-12.5
Micro-surfacing	Mixture of polymer-modified emulsion, mineral filler and dense-graded crushed fine aggregate, surface thicknesses range 10 to 20mm	Cure in less than one hour, fill rutting, and provide surface friction, seal crack, can be applied on pavement with poor condition	4-7	15-24
Cape Seal	Chip seal covered by a slurry seal or a microsurfacing	Provide a smooth, dense surface, good skid resistance and reduce noise	6-10	12-20
Thin Overlay	HMA with thicknesses of 13 to 38mm	Restore pavement ride quality	4-10	20-35

Another study conducted in Delaware suggest that the increased severity of either weather or traffic effect is sufficient to cause a drastic reduction in the treatment service life in thin overlay. The wide range of service life of thin overlay treatments is strongly depending on levels of weather severity, traffic, and route type. The service life of thin overlay is approximately 3 to 13 years when IRI is used as the performance indicator, 3 to 14 years for rutting, and 3 to 24 years for Pavement Condition Rating (PCR) [13].

Since the HMA thin overlay significantly improves pavement condition with a relatively high cost, a study by Dong suggested that microsurfacing could be a more cost-effective treatment. It is concluded that the cost-effectiveness of preservation decreases with the increase of traffic level and pre-treatment pavement deterioration [8].

Crack seals

Crack sealing is always the first line of defense in pavement preservation though it does not show significant improvement in long-term performance. Cohesion loss, adhesion loss and edge deterioration contributed highly to the overall failure in some crack seal treatment. Modified rubberized asphalt sealant may show long-term crack-seal performance (5-8 years) [14].

Crack sealing may provide the most cost-effective use of dollars over time in certain existing pavement condition compared to other pavement maintenance techniques. A study based on Pennsylvania local roads program concluded that roadways applied with crack seals have better rideability five years later than other surface treatments, such as chip seals, thin overlays and slurry seals [15]. A research used the data collected from 14 LTPP SPS-3 sites in Texas and investigated the effectiveness of four preventive maintenance treatments (crack seals, slurry seals, chip seals, and thin overlay). It was found that crack sealing was the best among the four preventive maintenance alternatives for low traffic routes with a sound underlying pavement structure [16].

Chip seals

High performance is observed in chip seals by extensive previous studies. Carvalho et al. analyzed the LTPP SPS-3 sites and found that the performance of chip seal was superior to thin overlay in freezing temperature zones, wet climates, and pavements with coarse subgrade [17]. A SPS-3 study using Texas sites found that chip seals performed well on a wide range of pavement conditions, and for most sites, was rated as the best treatment [16]. Shirazi et al. conducted a statistical analysis to compare the performance effectiveness of each treatment and concluded that the thin overlay and chip seal treatments were first options with respect to fatigue cracking [18]. Study conducted in Minnesota also discovered that chip seals may outfit thin overlay. It is forgiving and did not reflect the cracking that existed before the treatment applications [19].

The performance of chip seal is also sensitive to a variety of factors. Peshkin et al. concluded that the performance of chip seal in deep freeze zone is better than the performance in moderate freeze and no freeze zone [20]. Michigan DOT’s experience shows that chip seal may have poor performance under moderate to heavy commercial traffic because of aggregate loss and flushing. It points out that chip seal may result in a very rough surface that leads to significantly louder rolling noises of vehicle wheels [21].

Slurry Seals

Compared to the above three treatments, previous studies didn't draw attention on slurry seals. Eltahan et al. assessed the performance of each treatment in LTPP SPS-3 sections using survival analysis and a median survival time was computed as the number of years until 50 percent of the treatment sections fail. The median survival times for thin overlay, slurry seal, and crack seal were found 7.0, 5.5, and 5.1 years, respectively [22]. A recent study based on the observed roughness data in the LTPP SPS-3 sections found that the approximate life extension of the pavement sections benefited from the preservation treatments is: thin overlay for 5.4 years, chip sealing for 1.9 years, crack sealing for 1.7 years, and slurry sealing for 1.1 years [23]. Those results demonstrate the relative low effectiveness of slurry seal.

Specific findings from the 5-year evaluation of slurry seals under the LTPP SPS-3 study indicate that slurry seals perform better in warmer climates [24]. Peshkin et al.concluded that slurry seals have some influence on long-term roughness and rutting. They suggested that slurry seal should not be placed on pavements with moderate or severe cracks, or progressive rutting [20].

2.3 Factors Affecting Effectiveness of Preservation

Many factors contribute to the selection of an optimal treatment for an existing pavement. The factors may include existing pavement life, geography, distress severity, traffic levels, predetermined timetable, and available funding. For example, when a preventive treatment is applied, a pavement in relatively poor condition may receive higher performance jumps but higher deteriorate rate.

A survey conducted by NCHRP project 20-07 in US found that the five main purposes of the preventive maintenance are: reducing rate of deterioration, sealing surface, reducing water infiltration, increasing friction and smoothness. Most of the state agencies apply preventive treatment when the pavement is in the good and fair categories, but there are also some surprising responses: one agency reports that 60 percent of their treatments are placed on pavements in very good condition, while nine agencies report placing at least 30 percent of their preventive maintenance treatments on pavements in poor or very poor condition [25].

Performance and effectiveness of pavement preservation techniques may highly depend on the local traffic and climate conditions. Hein and Rao analyzed the cost-effectiveness of various preventive maintenance treatments using performance regression models. The results concluded that preventive treatments on the pavements in good condition last 1 to 2 years longer than preventive treatments on the pavements in fair condition, while preventive treatments for pavements with lower traffic last 0.5 to 1.5 years longer than preventive treatments for pavements with high traffic. In addition, chip seal and thin overlay seem more likely to succeed in different climates [9]. Wang et al. found that the effectiveness of the treatment varies significantly with climate zone and treatment types in terms of changes of IRI values. It was found that all the four types of treatments considered in the SPS-3 sites significantly reduced IRI development at two climate conditions: warm and dry or wet and cold [23].

Morian and Wang conducted a study to investigate the benefit–cost ratio of the treatments implemented at different years using life cycle cost [6]. Relevant results are generalized in Table 2. Results from PennDOT data indicate there is an optimum pavement age when the benefit-cost ratio associated with a treatment is maximized. Crack sealing, chip seal and microsurfacing reach their maximum effectiveness after five years of pavement construction. Crack sealing shows the highest benefit-cost ratio.

Table 2 Benefit-cost Ratio according to the Timing of the Treatment [6]

Preservation Type	Preservation Cost($ per lane mile)	Year Future Preservation Performed (year)	Extension life (year)	Benefit-Cost Ratio
Crack Sealing	2000	3	2	15.57
Chip Seal	10000	3	2.5	3.08
Microsurfacing	20000	3	3	1.42
Thin Overlay	30000	3	4	1.09
Crack Sealing	2000	5	4	34.18
Chip Seal	10000	5	5	7.55
Microsurfacing	20000	5	6.2	4.13
Thin Overlay	30000	5	7.5	2.99
Crack Sealing	2000	7	2	19.91
Chip Seal	10000	7	3	5.1
Microsurfacing	20000	7	4.5	3.39
Thin Overlay	30000	7	8.5	3.95
Crack Sealing	2000	10	1	11.82
Chip Seal	10000	10	2	3.98
Microsurfacing	20000	10	3	2.63
Thin Overlay	30000	10	7	4.06

2.4 Selection Guidelines of Preservation Used by State DOTs

Preservation treatment selection methods vary in state DOTs. For example, South Dakota DOT does not have any formal guidelines for choosing the most appropriate treatment for a certain pavement. Preventive treatments other than chip seals or sand seals have not been used except on an experimental purpose.

Pavement maintenance in South Dakota is generally a choice between chip seal and HMA overlay [26]. Typically, a chip seal is almost always placed between 3 and 5 years after placing the AC surface. The timing of the second application of chip seal is usually 6 to 8 years after the first application. A third chip seal may be applied occasionally since by that time the pavement is usually a candidate for a thin overlay.

The SDDOT developed the Enhanced Pavement Management System – Visual Distress Manual that detailed the distresses monitored and provided the definitions of various distresses for the selection of preservation treatments. It divides the crack into three 12 categories according to the severity and extents of cracking, as shown in Table 3 [27]. Each category is specifically defined related to the recommended maintenance treatment.

SDDOT's experience shows that pavements that are structurally deficient are not appropriate candidates for chip seals, since wide cracks or cracks experiencing large movements are expected to reflect through the chip seal treatment. Though chip sealing is predominantly used on low- to medium-volume roadways, several agencies are experimenting to installed chip seals on higher volume roadways [26].

Table 3 SDDOT's Selection of Maintenance Treatment

Pavement Distress	Severity Level	Extents	Cracking Sealing	Fog Seals	Srcub Seals	Micro-surfacing	Chip Seal	Thin HMA Overlay
Transverse Cracking	Low	Low	R	F	NR	R	R	NR
		Moderate	R	F	NR	R	R	NR
		High	F	F	NR	R	R	NR
		Extreme	NR	F	NR	R	R	NR
	Medium	Low	R	F	NR	F	F	F
		Moderate	R	F	NR	F	F	F
		High	F	NR	NR	F	F	R
		Extreme	NR	NR	NR	F	F	R
	High	Low	NR	NR	NR	F	NR	R
		Moderate	NR	NR	NR	F	NR	R
		High	NR	NR	NR	NR	NR	R
		Extreme	NR	NR	NR	NR	NR	R

R=Recommended; F=Feasible Treatment; NR=Treatment is not recommended
Severity level:
Low=Crack width is less than ¼ inch;
Medium=Crack width is greater than 1/4 inch and less than 1 inch;
High= Crack width is greater than 1 inch;
Extents:
Low=Crack spacing is greater than average spacing;
Moderate=Crack spacing is less than 50 feet and greater than 25 feet average spacing;
High= Crack spacing is less than 25 feet and greater than 12 feet average spacing;
Extreme= Crack spacing is less than 12 feet average spacing.

Guidelines in Illinois DOT and Ohio DOT also select treatments based on the distress severity [28, 29]. Table 4 shows the treatment selection table used by IDOT. However, the manual only can provide the basic selection recommendation. Under several categories, it may recommend the same available treatments. For example, the manual usually recommends crack seals, slurry seals, or chip seals in the pavement with low-severity distress. The recommended treatment in the pavement with medium- or high-severity distress is thin HMA overlay.

Table 4 IDOT's Selection of Maintenance Treatment

Pavement Condition	Distress Levels	Crack Sealing	Fog Seal	Sand Seal	Slurry Seal	Micro-surfacing	Chip Seal	Cape Seal
Fatigue Cracking	L1	F	NR	NR	F	F	F	F
	L2,L3,L4	NR	NR	NR	NR	NR	NR	NR
Rutting	N1,N2	NR	NR	NR	F	R	F	F
	N3	NR	NR	NR	NR	F	NR	NR
Transverse Cracking	O1	NR	F	R	F	R	R	R
	O2,O3	R	NR	NR	NR	F	F	F
	O4,O5	F	NR	NR	NR	NR	NR	NR
Longitudinal Cracking	Q1	R	F	F	F	F	F	F
	Q2,Q3	R	NR	NR	NR	F	F	F
	Q4,Q5	NR	NR	NR	NR	NR	NR	NR
Friction	Poor	NR	NR	R	R	R	R	R
ADT	<5000	R	R	R	R	R	R	R
	5000-10000	R	F	F	F	R	R	R
	>10000	R	NR	NR	NR	F	F	F
Relative Cost		$	$	$$	$$	$$	$$	$$

F=Feasible treatment but depends upon other project constraints including other existing distresses; NR=Treatment is not recommended to correct the specified pavement condition.

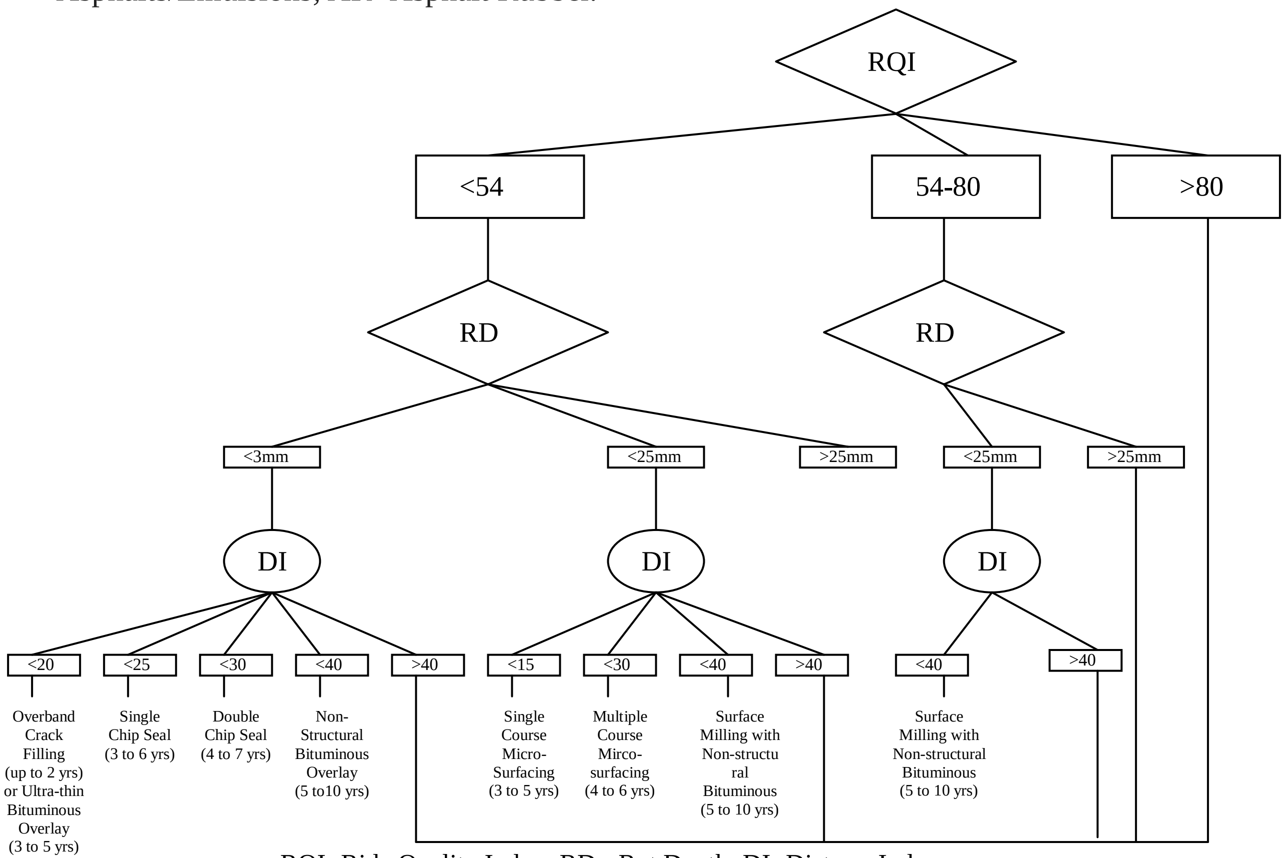
The treatment type is very specific in the guidelines used by Caltrans [30]. It considers the climate, traffic and geography effect. The same treatments are also specified according to the material, although these impacts on the selection of preservation treatments are not significantly different.

Some states develop their own pavement distress indicators and use them in the selection of preservation treatments. They also use decision tree model to incorporate a set of criteria for selecting a particular treatment through the "branches." Each branch represents a specific set of conditions [31]. For example, Michigan DOT develops RQI (Ride Quality Index) and DI (Distress Index) and uses them as the marginal value to select a specific treatment, as shown in Figure 2.

Table 5 Caltrans Asphalt Pavement Preservation Treatment Selection Guidelines

Treatment	Pavement Condition										Parameters												
				Rutting		Alligator					Climate				Traffic Volume								
	Raveling	Oxidization	Bleeding	<1/2"	>1/2"	0 to 10%	10 to 20%	20% to 30%	Longitudinal Cracking	Transverse Cracking	Desert	Vally	Coastal	Mountain	ADT<5000	3000<ADT<5000	ADT<3000	Night/Cold	Stop Point	Urban	Rural	high snow plow use	Cost of per lane mile($	Life Expectancy(year)
Crack Seal																							
Emulsion	N	N	N	N	N	F	P	N	F	F	G	G	G	G	G	G	G	N	G	G	G	G	2500	1-2
Modified (Rubber)	N	N	N	N		G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	2500	2-3
Fog Seal	F	G	N	N	N	F	P	N	P	P	G	G	G	G	F	N	N	P	F	G	G	F	4500	1
Slurry Seal																							
Type II	F	G	N	N	N	F	N	N	N	N	G	G	G	F	G	G	G	P	G	G	G	P	13000	3-4
Type III	G	G	N	G	G	F	P	N	N	N	G	G	G	F	G	G	G	N	G	G	G	P	13000	3-4
Microsurfacing																							
Type II	G	G	N	G	N	F	N	N	N	N	G	G	G	G	G	G	G	F	G	G	G	F	16000	3-4
Type III	G	G	N	G	G	F	P	N	N	N	G	G	G	G	G	G	G	F	G	G	G	F	16000	3-4
Chip Seal																							
PME-Medium, fine	G	G	N	F	N	G	F	N	P	P	G	G	F	F	G	G	N	N	P	P	G	P	6500	1-5
PME-Medium	G	G	N	F	N	G	G	N	P	P	G	G	F	F	G	N	N	N	P	P	G	P	6500	1-5
PMA-Medium	G	G	N	F	N	G	G	N	P	P	G	G	G	G	G	N	G	N	P	P	G	P	12500	4-5
PMA-Coarse	G	G	N	F	N	G	G	N	P	P	G	G	G	G	N	N	G	N	P	P	G	G	12500	4-5
AR-Medium	G	G	N	F	N	G	G	G	F	P	G	G	G	G	G	N	G	N	P	P	G	F	20000	4-6
AR-Course	G	G	N	F	N	G	G	G	F	P	G	G	G	G	N	N	G	N	P	P	G	G	20000	4-6
Thin Asphalt Overlay																							
Conventional	G	G	P	G	G	G	G	F	P	P	G	G	G	G	G	G	G	G	G	G	G	G	20000	3-5
PBA	G	G	P	G	G	G	G	G	F	F	G	G	G	G	G	G	G	G	G	G	G	G	25000	3-6
R(Type)	G	G	P	G	G	G	G	G	G	G	G	G	G	G	G	G	G	F	G	G	G	G	30000	5-8
Dig-outs	P	P	G	N	G	N	N	G	P	P	G	G	G	G	G	G	G	F	G	G	G	G	19000	5-8

G=Good; F=Fair; P=Poor; N=Not Recommended; PMA/PME=Polymer Modified Asphalts/Emulsions; AR=Asphalt Rubber.



RQI=Ride Quality Index; RD= Rut Depth; DI=Distress Index

Figure 2 Preventive Maintenance Decision Tree in Michigan DOT [32]

Similarly, Minnesota DOT creates its own practical network decision tree, as shown in Figure 3.

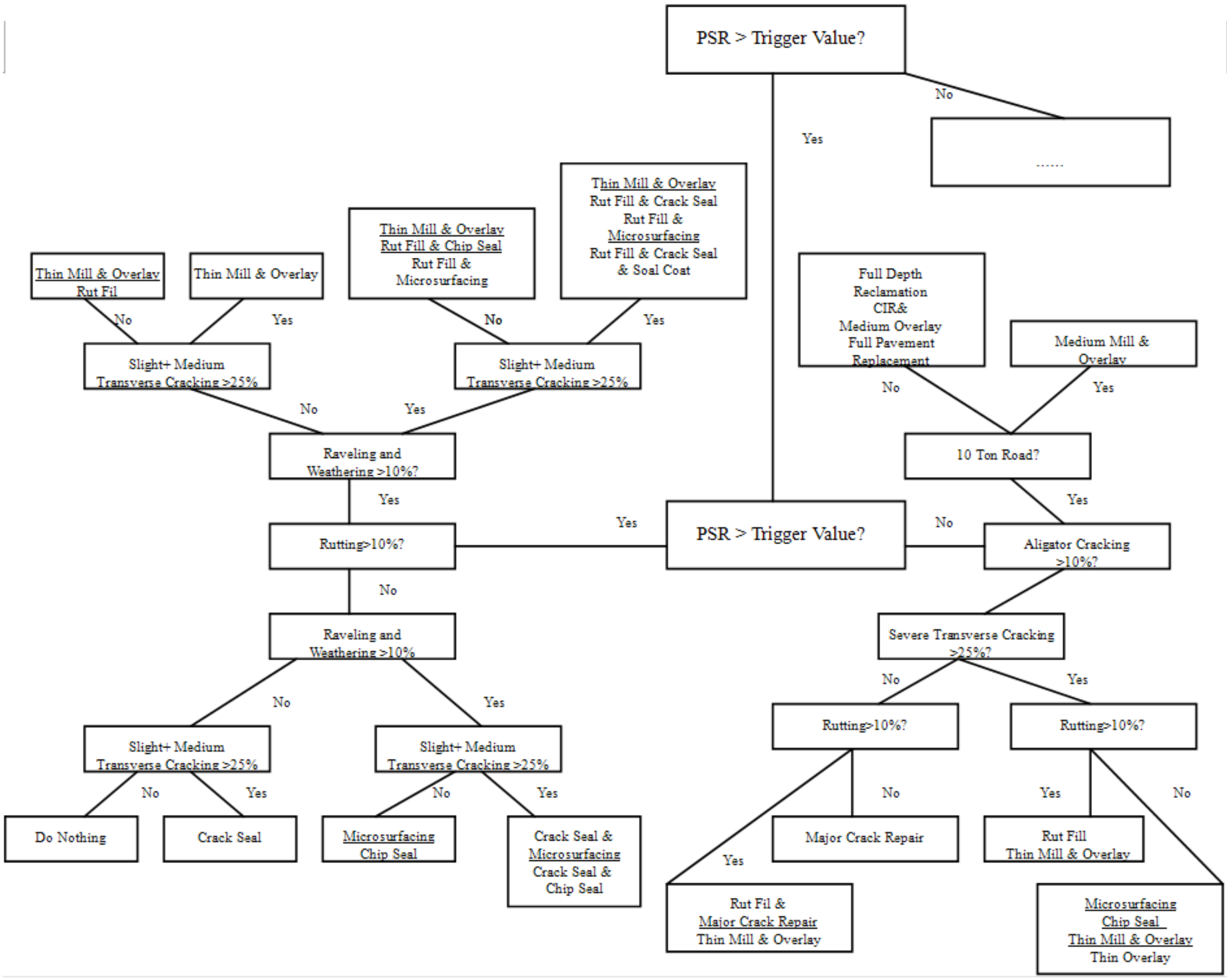


Figure 3 Network Level Decision Tree in Minnesota DOT [33]

It can be obtained from the above guidelines that common preservation treatments are crack seal, chip seal, slurry seal, microsurfacing, and thin overlay. Crack seal is always a favorable choice in low traffic condition and low crack severity. Chip seal and slurry seal can be applied in pavement with low or medium traffic and when crack severity is low. Thin overlay and microsurfacing are suitable for most conditions. From the perspective of pavement performance, most guideline can be simplified into the conclusions above. However, if cost is considered, the current guidelines may not select the most cost-effectiveness treatment.

A survey conducted in Canada found that a lack of information on the timing of preventative treatments and a lack of a standardized condition rating method between pavement management systems [34]. Researches recommend considering more factors in the selection of preservation treatment, including the type and extent of distress, traffic loading, climate, existing pavement type, cost of treatment, expected life, availability of qualified contractors, availability of quality materials, timing of placement, noise, and friction [8].

Davies and Sorenson studied the SPS-3 and SPS-4 sections in LTPP of the Southern Region in the U.S [35]. This study provides a more sophisticated decision matrix, as shown in Table 6.

Table 6 Guidelines for Effective Maintenance Treatment [35]

Pavement Conditions		Parameters	Thin overlay	Slurry Seal	Crack Seal	Chip Seal(Fine)	Chip Seal(Course)	Micro Surface	Fog
Traffic	ADT/Lane	<1000	E	E	E	E	E	E	E
		100<ADT<4000	E	E	E	E-Q	E-Q	E	E-Q
		>4000	E	E	E	E-N-Q	E-N-G	E	E-Q
	Ruts	<3/8in	E	E	E	E	E	E	E
		3/8in<R<1in	E	M-N	E	M-N-Q	M-N-Q	E	T
		>1 in	E	E	E	T	T	E	T
Cracking	Fatigue	Low	E	E	E	E	E	E	M
		Moderate	E	M	M	E	E	M	T
		High	M	T	T	E	E	T	T
	Longitudinal	Low	E	E	E	E	E	E	M
		Moderate	E	M	E	E	E	M	T
		High	E	T	M	M	M	T	T
	Transverse	Low	E	E	E	E	E	E	M
		Moderate	E	M	E	E	E	M	T
		High	M	T	M	M	M	T	T
Asphalt Surface Condition	Surface Appearance	Dry	E	E	T	E	E	E	E
		Flushing	E	E	T	M-Q	E	E	T
		Bleeding	E	E	T	N-Q	E-Q	E	T
		Variable	E	E	T	M-Q	N-Q	E	M
	Raveling	Low	E	E	T	E	E-Q	E	E
		Moderate	E	E	T	E	E	E	M
		High	E	M	T	E-Q	E	E	M
	Potholes	Low	E	E	T	E	E-Q	E	T
		Moderate	E	M	M	E	E	M	T
		High	M	M	M	E	M	M	T
Existing Pavement Texture is Rough			E	E	T	M-Q	M-Q	E	T
Poor Ride			E	E	T	T	E	M	T
Rural (minimum turning movement)			E	T	T	E	E	E	E
Urban (minimum turning movement)			E	E	E	E-Q	E-Q	E	E
High Snow Plow Usage			E	E	E	E-Q	E-Q	E	E
Low Frictional Resistance			E	E	T	E	E	E	T

E=Effective; M=Marginally effective; N=Not recommended; Q=Requires a higher degree of expertise and quality control; T=Not effective.

2.5 Summary

The chapter introduces the typical types of preventive treatments and summarizes previous studies on the effectiveness of preservation on pavement performance. The cost and the life extension data of different preventive treatments are collected. It can be observed that for most of the treatments, the life extension is highly correlated to the construction cost; while the cost is very sensitive to treatment thickness. For crack seal, cheap seal, and thin overlay, previous studies discovered their excellent performance in certain situations, which suggests that the performance of the treatment can be affected by environment, traffic and other factors.

The guidelines used by state DOTs to select preservation treatments were reviewed in this chapter. Crack seal, cheap seal, slurry seal, microsurfacing, and thin overlay are widely used in state DOTs' experience. Treatments such as sand seal, cape seal also show their potential effectiveness in the literature. It can be obtained that the selection guidelines generally provide several candidate treatments for a certain scenario. It is usually difficult to select the best preservation treatment from the guidelines. More efforts should be devoted to find the cost-effectiveness of preventive treatments with respect to the specific existing pavement distress.

Chapter 3 Effectiveness of Preservation on Different Pavement Distresses

3.1 Data Selection in LTPP Database

There are totally 81 LTPP SPS-3 sites distributed in the 33 states in the U.S. At each site four preservation treatments (thin overlay, slurry seal, crack seal and chip seal) were implemented on the pavement sections with the average length of 700ft and the average width of 24ft along with the control section. Therefore, the pavement sections with preservation treatments and the control section have the same climate and traffic conditions. To consider the major design factors influencing pavement performance, the experiment sites in the LTPP were specifically divided into 11 categories. The design factors for dividing categories include climate (precipitation and temperature), pavement structure (subgrade type and existing pavement condition) and traffic loading as defined by the LTPP program [12]. Several previous studies have investigated the performance of preservation treatments using all 81 sites. However, among these sites, the number of preservation treatment implemented at each site is basically different based on a recently published LTPP report [17]. For example, the slurry seal treatment in US 77 (N300 site) of Texas was used twice during four years of monitoring period while crack seal was applied 5 times during the same period. The analysis results could be biased without considering the number of treatment applied.

To better evaluate the performance of preservation treatments, this investigation only includes the specific sites having only one treatment applied during the monitoring period. After data filtering, there are 21 sites available. The distribution of the selected 21 sites is listed in Table 7. Each site is numbered with the name of the state where the section is located followed by a letter since there may be several test roadway sections in one state. For example, "MI-C" represents that the measurement is taken from test section C in Michigan. The site distribution subject to different design factors is not uniform with more sites in the wet region and only one site in the non-freeze region.

Table 7 Twenty-one SPS-3 Sites Selected for Distress Analysis

Existing Pavement Condition	Freeze Region							
	Wet Region				Dry Region			
	Fine Subgrade		Coarse Subgrade		Fine Subgrade		Coarse Subgrade	
	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic
Good	MD-A		MI-C					ID-B
	KY-A		MN-A					UT-C
			NY-B					ID-C
Fair	IA-A	IN-A			MT-A			
	KY-B				NE-A			
	MI-D							
Poor		VA-A	MN-B	PQ-A				
		ON-A		MN-C				
		MO-A						
Existing Pavement Condition	Non-freeze Region							
	Wet Region				Dry Region			
	Fine Subgrade		Coarse Subgrade		Fine Subgrade		Coarse Subgrade	
	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic	Low Traffic	High Traffic
Poor				FL-A				

The pavement distresses considered in the analysis include fatigue cracking, longitudinal cracking (both non-wheel path and wheel path), transverse cracking, and rutting. It is noted that the extent of fatigue cracking was measured as the percent (%)

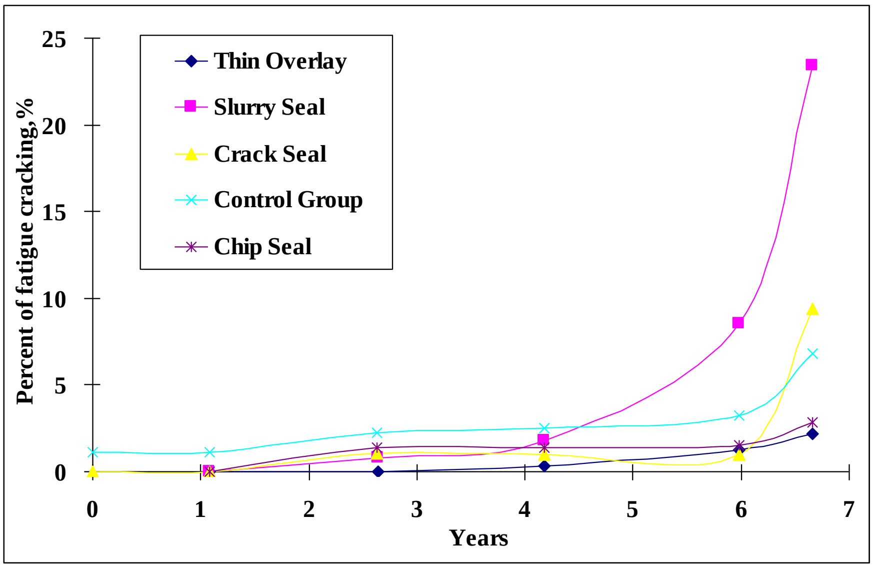
defined by the area of fatigue cracking divided by the area of the pavement section; while for longitudinal cracking and transverse cracking, the extents were measured as the length of cracking with respect to the length of wheel path (m/km). The rutting was measured as the depth of the surface depression in the wheel path (mm).

It is noted that the effectiveness of single preservation treatment may depend on the evaluation period. The shorter the evaluation period, the more favorable the short term solutions (such as crack sealing) would be; the longer the evaluation period, the more likely the more substantial treatments (such as thin overlay) would win out. Due to the availability of the LTPP data, the evaluation periods considered in this study vary from four to fourteen years for the selected 21 sites.

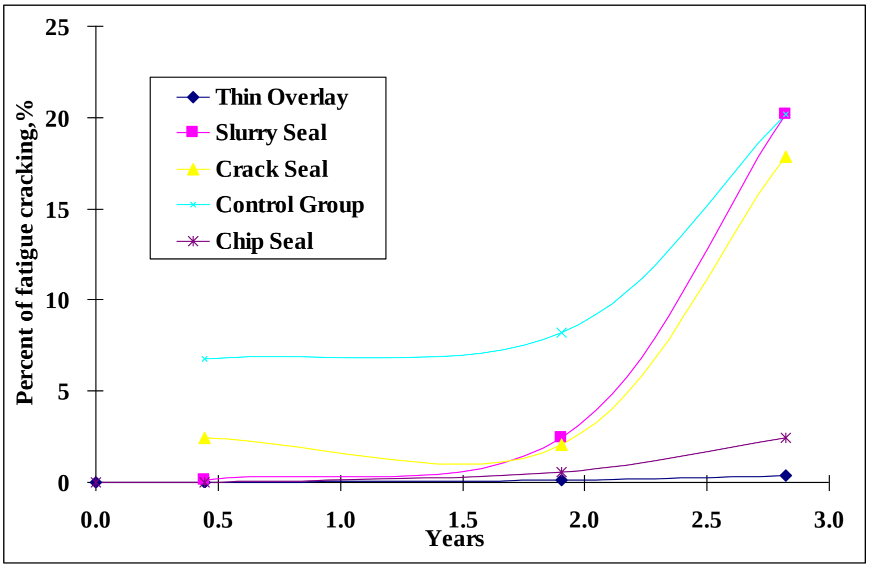
3.2 Development Trends of Pavement Distresses

The understanding of the development trend of pavement distresses is important for pavement performance prediction. Base on the distress data extracted from LTPP database, this section analyzed the development trend of various pavement distresses.

Fatigue cracking usually originated from the bottom of asphalt layer due to repeated traffic loading and indicates severe structure failure. Figure 4 shows the typical data observed for fatigue cracking. It was observed that when the area of fatigue crack is lower than 5%, the crack develops slowly. After the fatigue cracking area reaches 5% of the total area of the pavement, fatigue cracking starts growing rapidly. The plots show that slurry seal and crack seal only can retard fatigue cracking for a relatively short time period, compared to thin overlay and chip seal.



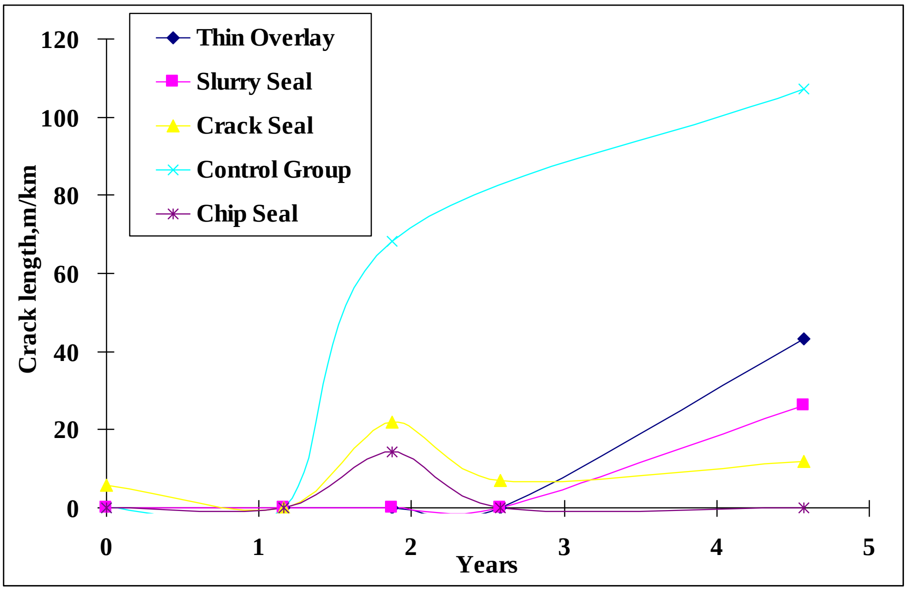
(a)



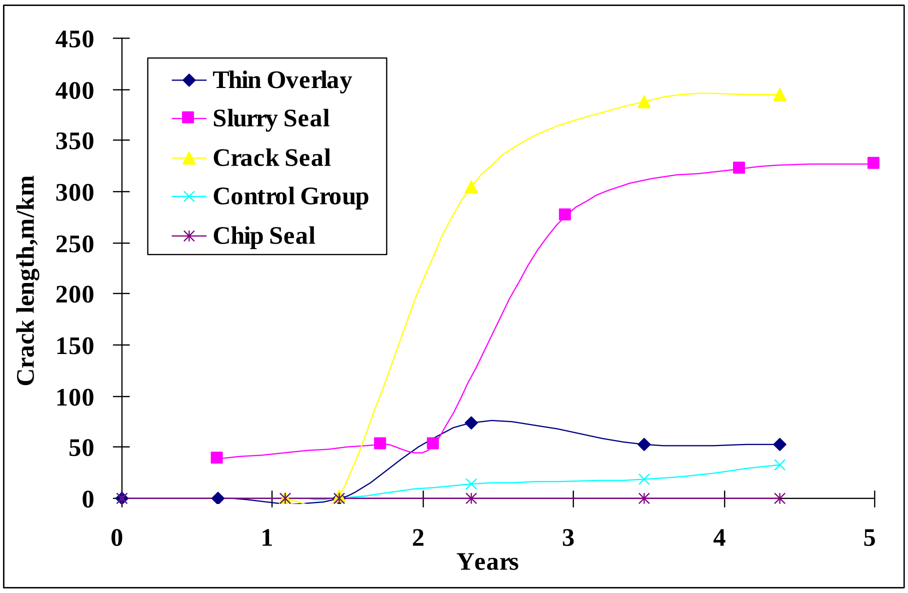
(b)

Figure 4 Development Trends of Fatigue Cracking at (a) NY State Route 3 and (b) IA State Route 196

Longitudinal cracking is the type of cracks parallel to pavement centerline either on or not on the wheel path. Longitudinal cracking usually appear as top-down cracking due to the combined effect of traffic loading, thermal loading, and asphalt aging. It was found that the development trend of longitudinal crack was different from the bottom-up fatigue cracking. As shown in Figure 5, the total longitudinal cracks in the wheel path and non-wheel path have a quick growth after 1-2 years and then have a relatively slow increasing trend.



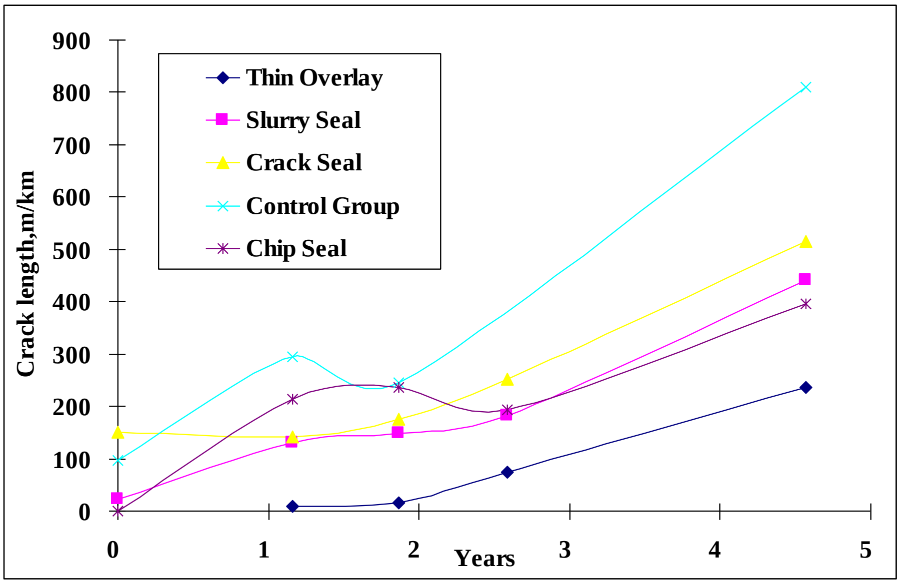
(a)



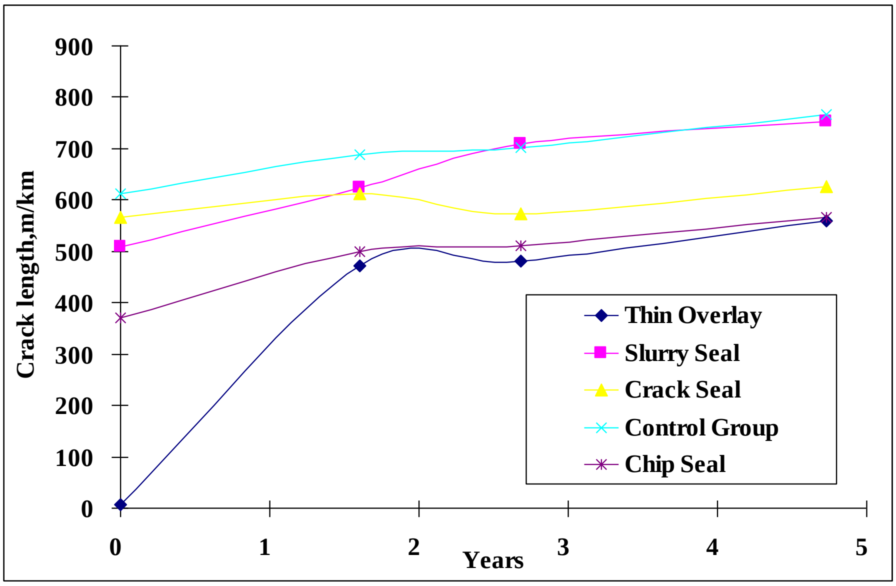
(b)

Figure 5 Development Trends of Total Longitudinal Cracks at (a) MI State Route 57 and (b) Interstate Highway 64

Transverse cracking is the type of cracks perpendicular to the pavements centerline and is a type of thermal cracking for non-composite pavements. Thermal cracking is mainly caused by the shrinkage of the asphalt surface due to low temperatures or asphalt binder hardening. As shown in Figure 6, the length of transverse cracks increases with the age of pavement in a relatively linear trend. The results show that the length of transverse cracks is approximately four times as long as the longitudinal crack in the pavement sections with thin overlay, slurry seal and crack seal, and ten times as long as the longitudinal crack in the control section and the section with chip seal.



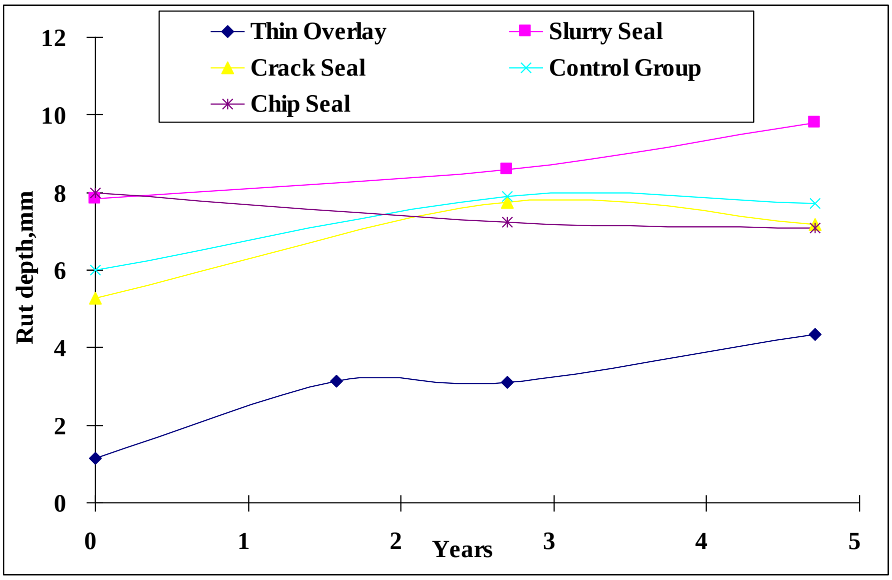
(a)



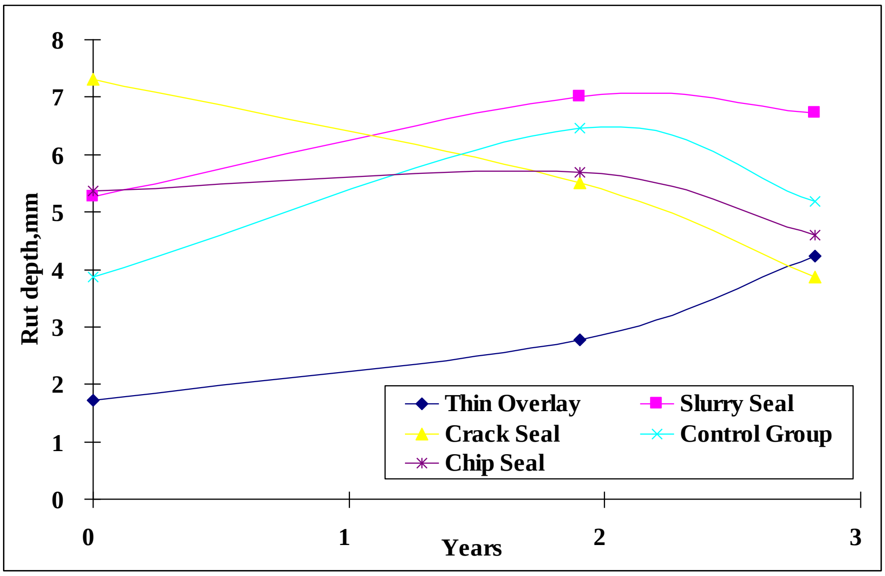
(b)

Figure 6 Development Trends of Transverse Cracking at (a) MI State Route 57 and (b) US 2

Rutting is the permanent deformation (compression or shear) in the wheel path caused by repeated vehicle loading. Figure 7 shows the development of rutting depth with year. It is clear that the pavement section with thin overlay has significant lower rut depth compared to other sections. After thin overlay, the initial rut depth becomes less than 2mm. However, the slopes of rut depth development were found identical for the section with thin overlay and the sections with other treatments.



(a)



(b)

Figure 7 Development Trends of Rutting Depth at (a) US 10 and (b) IA State Route 196

3.3 Quantification of Effectiveness of Pavement Preservation

The purpose of pavement preservation is to repair the existing pavement distresses and restore ride quality and skid resistance. The effectiveness of preservation treatments can be measured in short-term and long-term by using the attributes determined from the observed pavement performance with and without preservation treatments. Previous studies have used the performance jump or the deterioration rate reduction to evaluate the short-term effectiveness of preservation [36, 37]. The performance jump represents the change in performance measure just after the treatment (e.g. m/km for IRI or mm for rutting etc.); while the deterioration rate reduction is calculated as the difference in the slope of the deterioration curve before and after treatment. Figure 8 illustrates the concept of the reduction in the deterioration rate in response to different treatments and existing pavement conditions. It can be observed that the pavement with poor condition suffers higher rates of deterioration compared to the fair pavement. The figure also suggests the performance jump after the treatment is applied.

The long-term effectiveness of preservation treatments can be evaluated by using the treatment service life, the average pavement condition, and the area bounded by pavement performance curve [38, 39]. The treatment service life is determined from the treatment performance curve by extrapolating the curve to the point where the treated pavement reverts to an established threshold (depending on distress type or condition index). The average pavement condition can be determined in terms of percent change of the pavement condition after treatment relative to the pavement condition before treatment. The area bounded by the treatment performance curve for a specific distress is conceptually the most superior effectiveness measure since it represents both the average improvement in pavement condition and the extension in service life due to a preservation treatment.

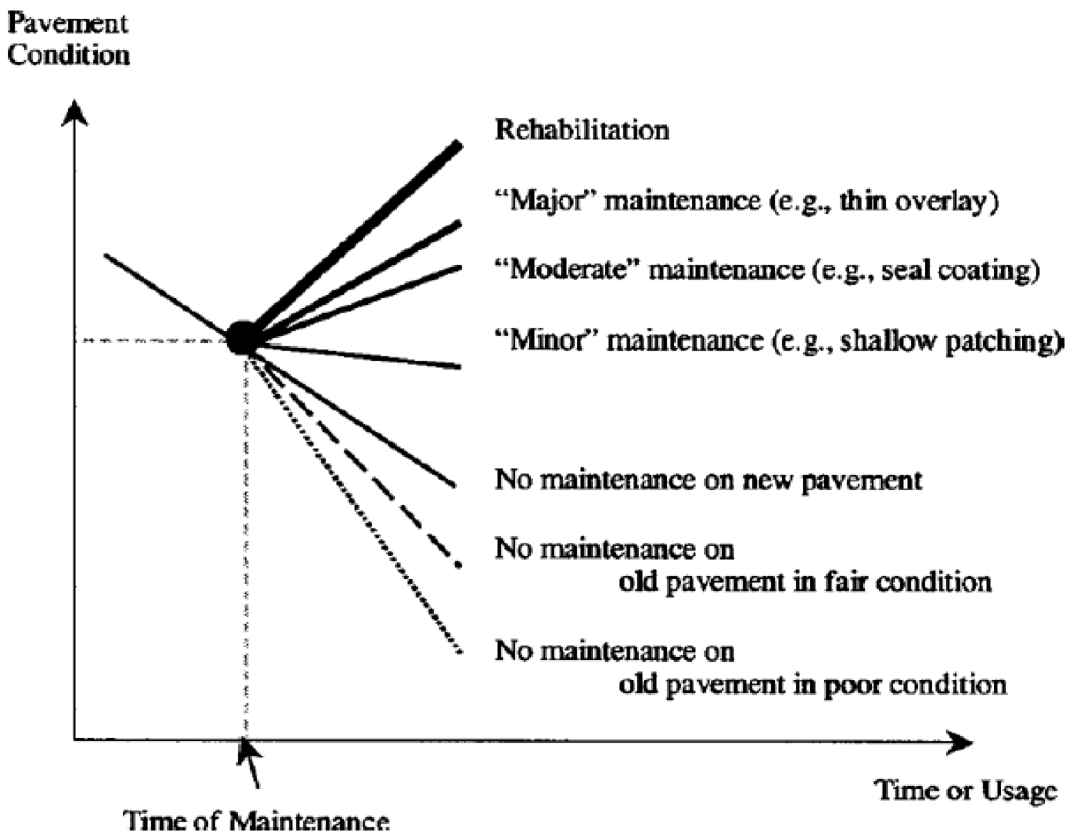


Figure 8 Illustrations of Deterioration Reduction Rate and Performance Jump after Maintenance [3]

In the LTPP database, the time intervals between two measurement points vary from three months to five years at different sites. The monitoring period ranges from four years to fourteen years while the available measurement points may vary from four to seven. In order to compare pavement distress with different monitoring intervals, an effective distress number (E-DN) was used, which was calculated as the weighted average of the distress number normalized over the total monitoring period

(Equation 1) [40]. The E-DN, in reality, represents the total area under the distress number versus time curve normalized by the total time period between the first and last measurements.

$$E-DN=\frac{\sum_{i=0}^{n-1}\frac{1}{2}(DN_i+DN_{i+1})\times\Delta Y}{Y_n-Y_1} \tag{1}$$

Where,

E-DN is the effective distress number that is the weighted value of distress number over the total monitoring period;

i is the survey number (i=0 is the initial distress number immediately after the treatment);

DN_i is the distress number measured at the ith survey;

ΔY is the period (in years) between survey i and survey i+1; and

n is the total number of surveys for the pavement section.

At each site, each pavement section with different preservation treatments and the control section have an E-DN representing the pavement distress condition over the total monitoring period. Then, a distress ratio (DR) is defined as the ratio of the E-DN after a certain treatment versus the E-DN of the corresponding control section (Equation 2). The DR is a very useful integrity indicator to reflect the effectiveness of preservation treatments compared to the control group. When the DR is smaller than 1, it means that the treatment mitigate pavement distresses and improve pavement serviceability. As different pavement distresses are measured in different units, the DR normalizes the effectiveness of preservation on individual distresses. The DR can be used to compare the effectiveness of preservation among different treatments for the same pavement distress or among different pavement distresses for the same treatment.

$$DR = \frac{E - DN_T}{E - DN_C} \tag{2}$$

Where,

DR is the distress ratio;

$E\text{-}DN_T$ is the effective distress number after a certain treatment; and

$E\text{-}DN_C$ is the effective distress number of the corresponding control section.

The calculated distress ratios for each treatment are listed in Tables 8-11, respectively, with respect to fatigue cracking, longitudinal cracking, transverse cracking and rutting. The results show that the distress ratios vary significantly among different sites. Thus it is difficult to compare the effectiveness of preservation treatment through the pairwise comparison of distress ratios between the specific sites. The effects of design factors on the effectiveness of preservation are mixed for different distresses and cannot get statistically verified due to the limited data.

Table 8 Summary of Distress Ratios for Fatigue Cracking

Pavement Condition	Freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Treatment	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH
Good	MD-A								MI-C							
	0.1	0.4	0.4	0.23					0	0	0.1	0				
	KY-A								MN-A							
	0	0	0.7	0					1	>6	1	0				
									NY-B							
									0.3	1.4	0.5	0.6				
Fair	IA-A				IN-A											
	0	0.5	0.5	0.1	>6	>6	>6	1								
	KY-B															
	1	1	1	1												
	MI-D															
	4.4	0	0	0												
Poor					VA-A				MN-B				PQ-A			
					0.2	4	>6	0	0.1	>6	4.7	0	0	0.4	0.2	0.1
					ON-A								MN-C			
					0	0.3	0.6	0.1					0	1.2	0	0
					MO-A											
					0.7	0.8	0.2	0								
Pavement Condition	Freeze and Dry Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Good													ID-B			
													1	1	1	1
													UT-C			
													0.2	>6	2.2	0.2
													ID-C			
													0	0	0.1	0
Fair	MT-A															
	>6	>6	>6	1												
	NE-A															
	>6	1.7	0	1												
Pavement Condition	Non-freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Poor													FL-A			
													1	>6	>6	4.3

Table 9 Summary of Distress Ratios for Longitudinal Cracking

Pavement Condition	Freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Treatment	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH
Good	MD-A								MI-C							
	1.1	0.6	1.1	0.1					0.1	0.7	1	0.1				
	KY-A								MN-A							
	0	>6	3.7	0					>6	>6	1	>6				
									NY-B							
									0.3	1.4	0.5	0.6				
Fair	IA-A				IN-A											
	0.2	0	1.4	1	0.2	0.7	2.2	0								
	KY-B															
	0	0.2	1.4	0												
	MI-D															
	0.2	0.9	1.1	0.8												
Poor					VA-A				MN-B				PQ-A			
					0.1	1	1.1	0.4	0.4	0.6	1	0.6	0.7	0.5	1.1	1.2
					ON-A								MN-C			
					0.3	0.7	2	0.2					0.6	0.7	0.8	1
					MO-A											
					0.4	0.7	1	0.4								
Pavement Condition	Freeze and Dry Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Good													ID-B			
													1.3	6	1	1
													UT-C			
													>6	>6	>6	>6
													ID-C			
													6	6	0.1	0.4
Fair	MT-A															
	>6	>6	>6	>6												
	NE-A															
	0.4	0.4	0.4	0.1												
Pavement Condition	Non-freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Poor													FL-A			
													3.1	5.4	>6	1.3

Table 10 Summary of Distress Ratios for Transverse Cracking

Pavement Condition	Freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Treatment	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH
Good	MD-A								MI-C							
	0.2	4.2	3	0					0	0	0.3	0				
	KY-A								MN-A							
	0	>6	1.8	0					>6	>6	1	>6				
									NY-B							
									0.3	0.1	0.7	0.6				
Fair	IA-A				IN-A											
	1	0.1	1.3	1.1	0.6	1.5	1.8	0.3								
	KY-B															
	1	4.3	2	0												
	MI-D															
	0.2	0.5	0.6	0.6												
Poor					VA-A				MN-B				PQ-A			
					0	2.2	>6	0	0.6	0.9	0.9	0.7	0.7	0.6	1	0.7
					ON-A								MN-C			
					0.8	1.2	>6	0.8					0.6	1	1	0.8
					MO-A											
					0.1	0.8	0.9	0.4								
Pavement Condition	Freeze and Dry Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Good													ID-B			
													2	1	1	>6
													UT-C			
													1	1.5	1.7	0.4
													ID-C			
													1.1	0.9	0.6	0.9
Fair	MT-A															
	2.2	1.2	2.1	1.9												
	NE-A															
	1.1	0.9	0.7	1												
Pavement Condition	Non-freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Poor													FL-A			
													>6	>6	>6	>6

Table 11 Summary of Distress Ratios for Rutting

Pavement Condition	Freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Treatment	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH	TH	SL	CR	CH
Good	MD-A								MI-C							
	0.2	1	1	0.04					0.3	1.1	1.4	0.7				
	KY-								MN-A							
	0	0.9	1	1.11					1.3	>6	>6	2.1				
									NY-B							
									0	0.1	0.1	0.5				
Fair	IA-A				IN-A											
	0.5	1.2	1.2	1	0.3	1	1	0.9								
	KY-B															
	0.8	1.2	0.9	1.48												
	MI-D															
	0.1	1.2	1.1	1.05												
Poor					VA-A				MN-B				PQ-A			
					0.2	0.4	0.5	0.4	0.4	1.7	1.2	1.3	0.2	0.6	1	0.3
					ON-A								MN-C			
					0.2	0.5	1.3	0.7					0.4	1.2	1	1
					MO-A											
					0.3	1.1	0.9	0.9								

Pavement Condition	Freeze and Dry Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Good																
Fair																
	NE-A															
	0.2	0.9	1.1	0.64												

Pavement Condition	Non-freeze and Wet Region															
	Fine Subgrade								Coarse Subgrade							
	Low Traffic				High Traffic				Low Traffic				High Traffic			
Poor													FL-A			
													0.8	2.3	2	2.8

It is noted that the column with “>6” suggests that the calculated distress ratio is greater than six. This is usually due to the effective distress number (E-DN) in the control section is close to zero while the E-DN in the section with preservation treatment is not zero. These data could be caused by the measurement error and thus were not considered in the analysis since there is no reason that the preservation would cause the significant increase of pavement distress.

3.4 Effectiveness of Preservation Treatments on Pavement Distresses

Descriptive statistics analysis was first conducted to evaluate the effectiveness of pavement preservation to different pavement distresses. Figures 9-12 show the boxplots of the calculated distress ratios with respect to different distresses, respectively, for thin overlay, slurry seal, crack seal, and chip seal. Boxplot is a convenient way of graphically describing groups of numerical data through five statistical indexes: the minimum sample value, the lower quartile (Q1), the median (Q2), the upper quartile (Q3), and the maximum sample value.

The results show that the distress ratios after pavement preservation vary depending on the treatment type and the specific pavement distress. In terms of the median values of the distress ratios, all four treatments have the smallest distress ratio for fatigue cracking but the greater distress ratio for transverse cracking. This trend is most noticeable for the section with crack sealing. This suggests that in general pavement preservation has better effectiveness to prevent the load-related fatigue cracking compared to the non-load related temperature cracking.

On the other hand, the interquartile range (IQR) and the length of whisper in the boxplot show that the distress ratios vary significantly within a wide range even for the same type of treatment for a specific pavement distress. This is probably because the effectiveness of preservation may vary depending on route type, pavement structure, climate condition, and traffic level at different LTPP sites. The calculated distress ratios for cracking show higher variations than the distress ratios for rutting, with the distress ratios for transverse cracking showing the highest variation.

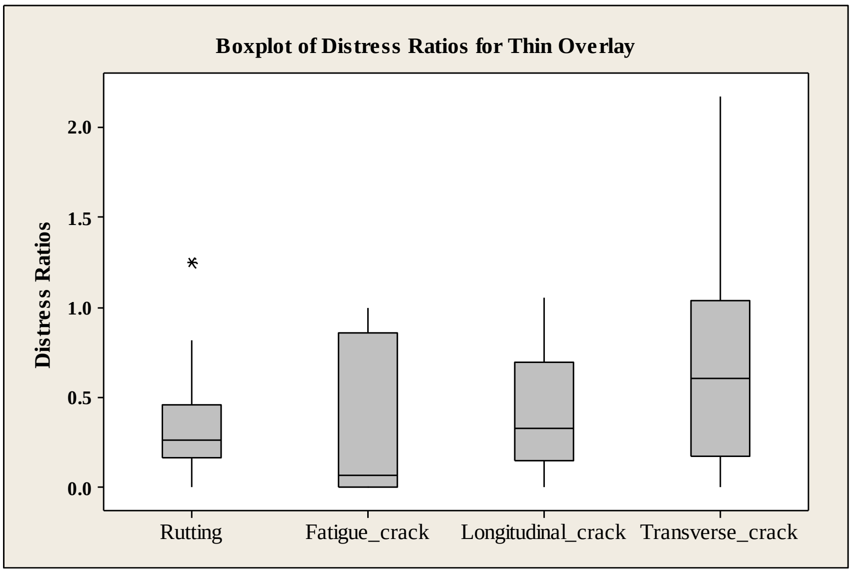


Figure 9 Distress Ratios for Thin Overlay

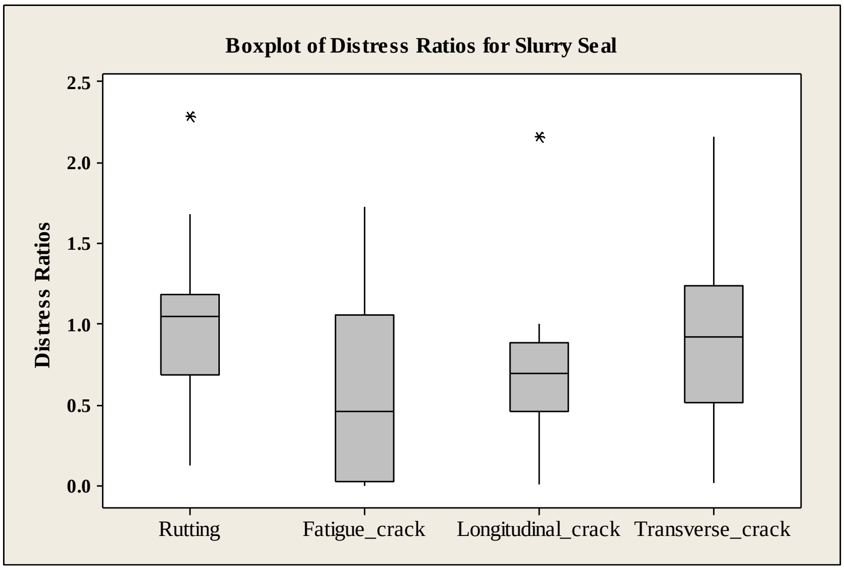


Figure 10 Distress Ratios for Slurry Seal

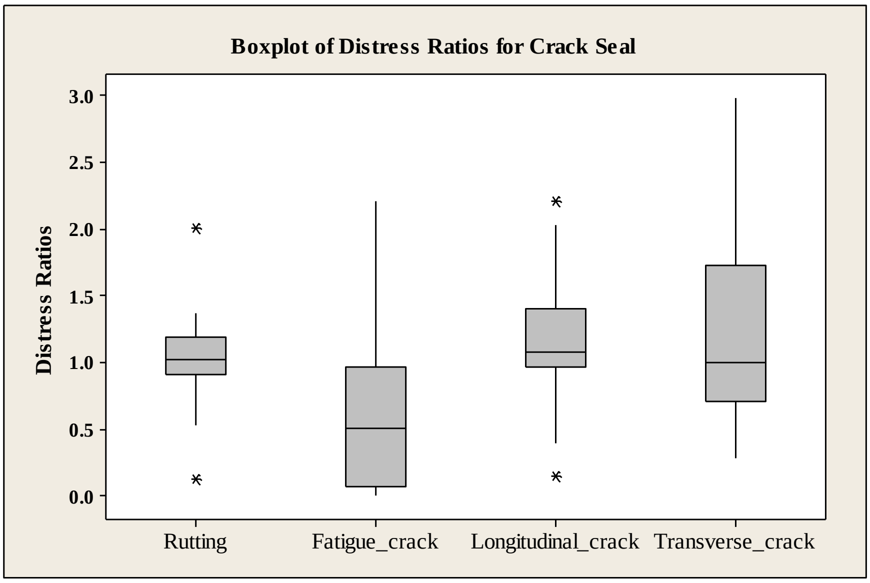


Figure 11 Distress Ratios for Crack Seal

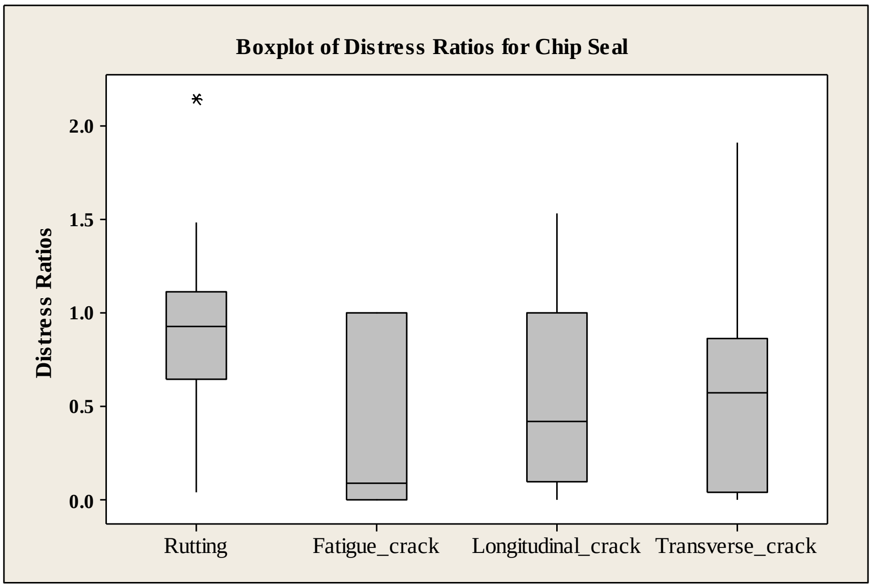


Figure 12 Distress Ratios for Chip Seal

To identify whether a certain treatment has statistically significant effectiveness on the specific pavement distress, a variety of statistical methods can be used. Since the data are only selected from 21 sites, and some of the data sets are skew distributed, the non-parametric test becomes a reasonable choice in this scenario. Consequently, the Friedman test is preferred in the analysis. It can be used for multiple comparisons without making assumptions on the distribution of the data (e.g. normality) [50]. In this study, the DR values for each treatment with respect to each performance indicator are compared to 1.0 with the critical p-value of 0.05. An example of the Friedman test result is shown in Table 12. Since the p-value is closed to zero, it can be concluded that the slurry seal has significant effectiveness in retarding longitudinal cracking.

Table 12 Example of the Friedman Test Output

S = 9.60 DF = 1 P = 0.002			
Treatment	N	Estimated Median	Sum of Ranks
Threshold	15	1	28.5
Slurry Seal	15	0.6925	16.5
Grand Median=0.8463			

Table 13 summarizes the test results for the effectiveness of preservation treatments. The symbol of “Y” indicates that the DR is significantly smaller than 1.0 and the symbol of “N” indicates that the DR is not significantly smaller than 1.0. The results show that thin overlay shows significant effectiveness in all four performance indicators. Chip seal shows significant effectiveness in three performance indicators except rutting. Slurry seal shows significant effectiveness in retarding longitudinal cracking; while crack seal shows significant effectiveness in retarding fatigue cracking. As consistent with the previous studies using LTPP data, only thin overlay shows significant effectiveness in preventing rutting.

The results presented in Table 13 can be used to help select the appropriate preservation treatment based on the specific existing pavement distress. For example, if both fatigue cracking and transverse cracking are identified as the major distresses in the existing pavement, the appropriate treatment could be thin overlay or chip seal;

while if the rutting is the major distress, the appropriate treatment could only be thin overlay. Agencies may also choose to use the way they prefer based on the most critical distress at their regions.

Table 13 Friedman Test Results for Effectiveness of Preservation Treatments

Distress type	Thin overlay		Slurry seal		Crack seal		Chip seal	
	Significance	p-value	Significance	p-value	Significance	p-value	Significance	p-value
Fatigue cracking	Y	0.002	N	0.109	Y	0.006	Y	0.002
Longitudinal cracking	Y	0.001	Y	0.002	N	0.467	Y	0.039
Transverse cracking	Y	0.044	N	0.453	N	1	Y	0.005
Rutting	Y	0.000	N	0.317	N	1	N	0.439

3.6 Summary of Findings

Pavement preservation can retard the development of pavement distresses and improve pavement performance. This chapter analyzed the effectiveness of pavement preservation on different pavement distresses including fatigue cracking, longitudinal cracking, transverse cracking, and rutting. The following findings can be concluded from the analysis:

1. The development trend of fatigue cracking is different from other distresses, such as transverse cracking and rutting. The length of transverse cracks in the pavement is much greater than the length of longitudinal cracks, especially in the sections with chip seal and the control sections.

2. Thin overlay shows significant effectiveness in all four performance indicators (fatigue cracking, longitudinal cracking, transverse cracking, and rutting). Chip seal shows significant effectiveness in three performance indicators except rutting. Slurry seal shows significant effectiveness in preventing longitudinal cracking; while crack seal shows significant effectiveness in preventing fatigue cracking.

3. In general, pavement preservation has better effectiveness to prevent the load-related fatigue cracking compared to the non-load related temperature cracking. The effectiveness of preservation vary significantly depending on route type, pavement structure, climate condition, and traffic level at different LTPP sites. The higher variations were observed in the effectiveness of pavement preservation in preventing cracking compared to rutting.

Chapter 4 Effectiveness of Preservation on Pavement Surface Friction

4.1 Background on Pavement Friction

Pavement friction is a complex phenomenon and affected by many factors, including material, traffic, environment, and etc [5]. For example, the pavement surface properties such as aggregate sizes, gradation, asphalt binder content, produce different macro- and micro-texture that attribute to the variation of friction at different speeds after cumulative traffic passing. It has been established that good micro-texture is important for pavement friction at low speeds and good macro-texture is more important at high speeds [41, 42].

Many environmental aspects influence pavement friction, such as rainfall, snowfall and temperature. Previous studies concluded that when the friction testing was conducted in wet regions, the water film may cover the pavement surface and act as a lubricant, which can reduce the contact between the tires and surface aggregate. This is one of the reasons why wet-pavement surfaces exhibit lower friction than dry pavement surfaces [43]. Some researchers attributed the seasonal variation of friction to rainfall. The reason is that the rainfall is low and the evaporation rates are higher in the spring and early summer, which may impair the function of rainwater to remove lubricating agents and contaminants on the surface of roadway [44]. On the other hand, McDonald et al. found that the contribution of snowfall removal and winter weather highway operations to the seasonal variation of pavement friction is relatively negligible compared to the effect of temperature [45].

Most previous studies agree that air temperature affects flexible pavement friction because both the tire rubber and the asphalt mixture are viscoelastic materials. The variation of viscoelastic modulus due to temperature change will affect the contact mechanism at the tire-pavement surface. Flintsch et al. found that both friction parameters (friction number at zero speed - SN0 and percent normalized gradient - PNG) in the Penn State model tended to decrease when the pavement surface temperature increased [46]. Additionally, the temperature effects on the friction number were relevant to the testing speed. Bazlamit and Reza showed that the hysteresis component of friction decreased with the increasing temperature whereas the adhesion component increased with the increasing temperature and had a high influence on the overall friction [47]. They proposed an equation to adjust the friction numbers measured at different temperatures where every 1°C below 20°C caused 0.2 unit of increase in friction number compared to the friction number at 20°C. Similarly, another study concluded that every 1°F below 80°F caused 0.08 unit of increase in friction number compared to the friction number at 80°F [48].

4.2 Data Collection in LTPP Database

In the totally 81 LTPP SPS-3 sites, the friction monitoring data are available in the 53 sites because the collection of friction data in LTPP is voluntary for agencies. The number of sites in each category having friction monitoring data available is shown in Figure 13. It should be noted that Texas consists of 14 sites which cover all of the 11 categories; while most states only have a few sites in some specific categories.

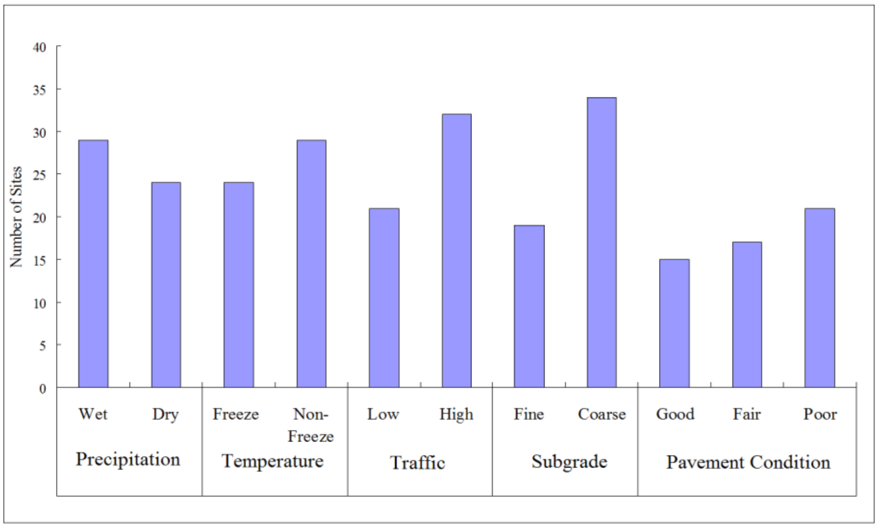


Figure 13 Number of SPS-3 Sites Having Friction Data in Each Design Category

Figure 14 lists the number of sites with different measurement points of pavement friction in the LTPP database. At each site, the pavement sections with different preservation treatments have the same number of measurement points measured at very similar climate conditions because the friction tests were conducted at these sections subsequently within the same day. The time period between successive friction measurements ranges from two months to four years, depending on the monitoring frequency at specific sites. The time spans of the total 53 sites vary from three years to seven years and the monitoring periods at most sites are within two to four years. It is expected that the effects of pavement age on friction degradation are related to both traffic loading and weather variation.

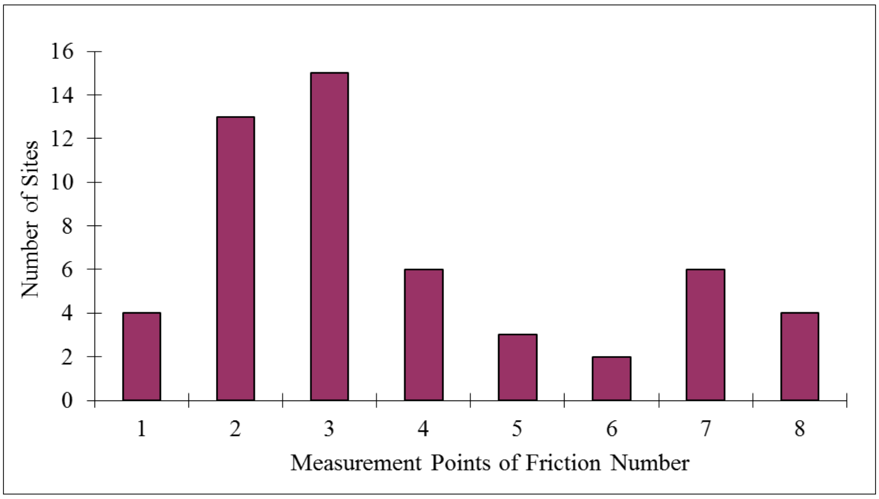


Figure 14 Number of Sites with Different Measurement Points of Friction Number in SPS-3

Various factors that may affect pavement friction were collected from the LTPP database. These are climate factors (air temperature at friction testing, annual average temperature, freeze index, precipitation), surface material properties (percentage passing No.200 sieve, percentage passing No.4 sieve, asphalt content). The traffic and climate data were obtained from the General Pavement Study (GPS) sites near the relevant SPS-3 sites (The SPS-3 sites and the relevant GPS sites are in the different sections of the same roadway). The Equivalent Single Axle Load (ESAL) was used as the traffic volume unit. The freeze index is defined as the sum of the average daily air temperature on the day when average daily temperature is below freezing. It is noted that the percentages passing No.200 sieve and No.4 sieve were found only in the pavement sections treated with slurry seal and chip seal. No material data were found available in other sections such as air void, voids in mineral aggregate (VMA), and gradation.

The friction measurement device used in the LTPP program is locked wheel skid tester. The locked wheel friction measuring devices provide a coefficient of friction that is typically reported as friction number (or skid number) [41]. The friction number is calculated as the ratio of the measured horizontal force at the tire-pavement interface with respect to the normal force on the tire as the tire is fully locked. Only the friction number measured at 64km/h is used and thus the speed effect on the friction is not considered in the analysis.

Table 14 shows the statistics summary of friction data and other traffic, climate and material parameters. Since a wide range of friction number was observed, the friction data of all sections were individually checked for accuracy, practicality, and consistency. Some extreme values in friction number were excluded from the analysis, such as unusual increases or decreases. For example, at one site the friction number increases by 30 units within six month, which may be due to measurement error.

4.3 Effect of Preservation on Friction Improvement

To evaluate the effectiveness of preservation treatments on pavement friction, different performance indicators can be used, such as change of friction immediately after treatment, change of friction degradation slope, average friction over the monitoring period, and etc. Similar with the distress measurements, the time period between two measurement points of friction vary from less than six months to four years in the LTPP database. In order to compare pavement friction with different monitoring intervals, an effective friction number (E-FN) was used, which was calculated as the weighted average of the friction number normalized over the total monitoring period (Equation 3). The effective friction number, in reality, represents the total area under the friction number versus time curve normalized by the total time period between the first and last measurements. This concept is similar to the effective distress number concept used in the evaluation of pavement condition. After the calculation, each preservation treatment at each site has an effective friction number representing the pavement friction performance over the total monitoring period.

Table 14 Summary of the LTPP SPS-3 Data for Friction Analysis

Statistics	Count	Min.	Max.	Mean	Standard Deviation
Friction Number (FN)	946	17	85	45	11
Age, years	200	1	8	6.6	4.8
Annual Traffic, 1000 ESAL	200	10	2729	185.5	349.2
Air Temperature at Friction Testing, °F	200	33	110	74.6	14.2
Annual Avg. Temperature, °C	200	1.6	23.2	15.8	5.2
No. 200 Sieve Passing*, %	159	0	1.9	5.7	5
No. 4 Sieve Passing*, %	159	59	70	45.6	41.4
Asphalt Content, %	369	3.6	8.8	5.7	0.9
Annual Precipitation, mm	200	114	1979	914	419
Freeze Index	200	0	1872	166	319

* Data for chip seal and slurry seal only.

$$E - FN = \frac{\sum_{i=0}^{n-1} \frac{1}{2}(FN_i + FN_{i+1}) \times \Delta Y}{Y_n - Y_1} \tag{3}$$

Where,

E-FN is the effective friction number that is the weighted value of friction number over the total monitoring period;

i is the survey number (i=0 is the initial friction number immediately after the treatment);

FN_i is the friction number measured at the ith survey;

ΔY is the period (in years) between survey i and survey i+1; and

n is the total number of surveys for the pavement section.

Descriptive statistics analysis was first conducted to compare the friction performance due to four preservation treatments. Figure 15 shows the boxplot of the effective friction numbers measured at the sections with preservation and the control section.

From the boxplot results, the sections with slurry seal clearly demonstrates higher friction values than the control sections; while the effect of other three treatments on friction improvement cannot be distinguished compared to the control group. In addition, the results show that the friction data in the sections with thin overlay and chip seal show the relatively lower variations; while the section with crack seal shows the highest variation in the friction number. The reason for the high friction in the sections with slurry seal may be that the mixture of emulsion asphalt and aggregate can lead to a combination of good micro- and macro-texture. The friction performance of chip seal is relatively poor in this study. This could be due to the loss of aggregate chips after traffic passing thus causing a binder-rich surface. This is consistent with the finding from a previous study on Maryland road network, which shows the differences of friction number between the slurry seal and other preservation treatments (mainly are thin overlays) are 5~8 units when the traffic intensity varies in a wide range [49].

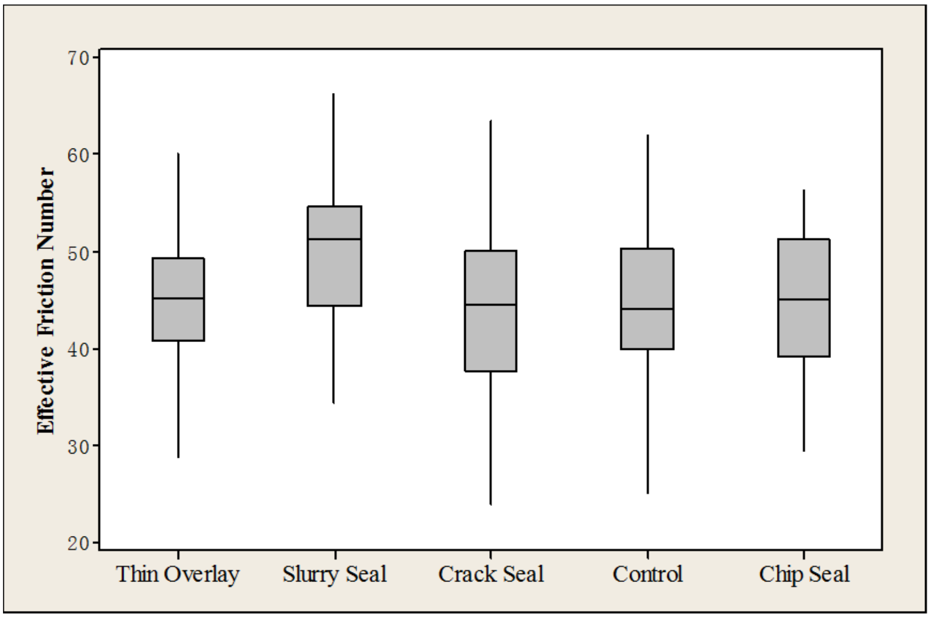


Figure 15 Boxplot of Effective Friction Number for Various Preservation Treatments

Ranking method is used to further compare the friction improvement after different preservation treatments using the effective friction number (E-FN) calculated at each site. The treatment causing the highest friction number was given a score of 5; while the treatment causing the lowest friction number was given a score of 1. The same score was given to the two or more treatments causing the same friction number (differences smaller than 0.3 in this study). Table 15 shows ranking results for the 53 sites categorized based on five design factors. After the ranking, the average scores for each treatment are: slurry seal (4.12), chip seal (3.15), thin overlay (3.10), and crack seal (2.50). In general, the preservation treatments cause higher friction numbers than the control group to a certain extent, except for the crack seal. Consistent with the result from the boxplot results, slurry seal causes the most effective friction improvement among four preservation treatments.

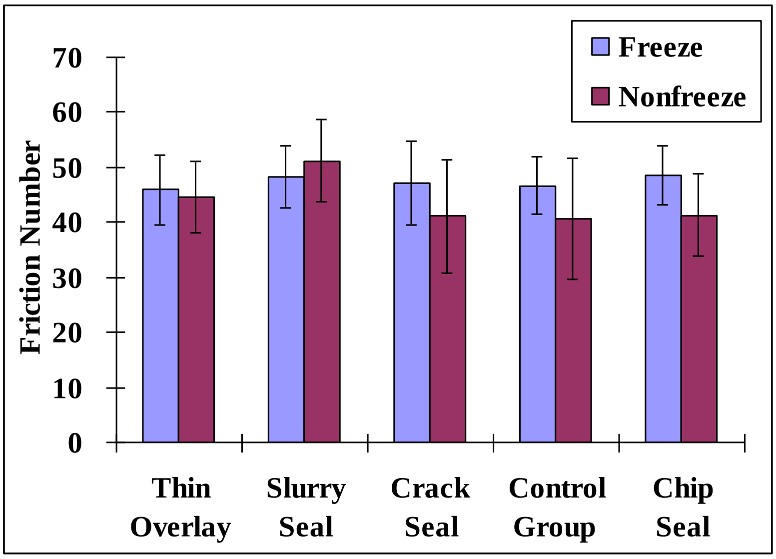
Table 15 Ranking Results of Preservation Treatments on Friction Improvement

Wet	**Freeze**																							
	Fine												**Coarse**											
	Low						**High**						**Low**						**High**					
		TH	SL	CR	CO	CH		TH	SL	CR	CO	CH		TH	SL	CR	CO	CH		TH	SL	CR	CO	CH
Good	MD	5	1	3	4	2							MI	5	1	2	3	4						
	IL	3	5	2	4	1							MO	1	4	2	3	5						
													NY	2	3	1	5	4						
Fair	MI	3	2	5	1	4	IN	5	4	1	2	3												
							MI	2	3	5	4	1												
Poor							MO	1	5	2	3	4	IL	3	5	1	2	4	NY	2	4	3	5	1
																			PA	1	2	4	5	3
																			MI	4	5	2	3	1
Wet	**Non-freeze**																							
Good							AR	4	5	NA	NA	NA	TX	4	5	3	2	NA						
							TX	3	5	2	1	4	TX	2	3	4	5	1						
													MI	5	4	2	3	1						
Fair	TX	1	5	2	3	4	OK	3	5	4	NA	2							AL	2	3	4	5	1
																			AL	4	5	2	3	1
																			OK	4	5	3	NA	2
																			TX	2	5	4	NA	3
Poor							TX	4	5	2	1	3							AL	4	2	5	3	1
																			FL	4	5	3	NA	2
																			FL	2	5	4	NA	3
																			FL	4	5	3	NA	2
Dry	**Freeze**																							
Good																			UT	3	4	2	NA	5
Fair	MT	2	4	5	NA	4													NV	2	3	5	1	4
	NE	1	4	3	2	5													NV	5	3	2	NA	4
Poor	CO	5	2	3	1	5	SK	4	5	1	2	4	UT	2	4	5	NA	3	SK	5	3	2	2	4
													UT	2	4	3	NA	5						
													NV	2	4	3	NA	5						
Dry	**Non-freeze**																							
Good	TX	4	5	1	2	3							TX	4	5	1	2	3	TX	4	5	2	NA	3
																			TX	4	5	1	2	3
Fair	TX	4	5	2	3	1													AZ	3	2	4	NA	5
	TX	3	5	2	1	4													TX	3	5	1	2	4
Poor							OK	NA	5	2	4	3							AZ	3	2	5	NA	4
																			AZ	3	2	4	NA	5
																			AZ	5	1	3	4	2
																			TX	4	5	1	2	3

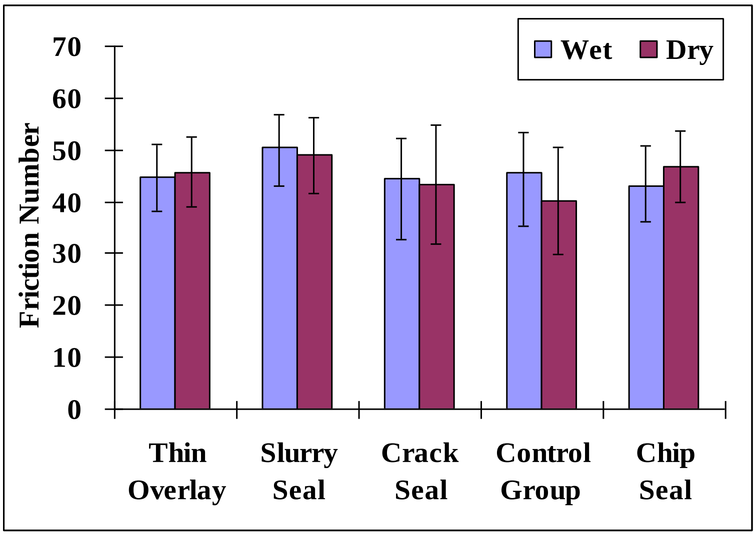
*(TH=Thin Overlay, SL=Slurry Seal, CR= Crack Seal, CO= Control Group, and CH=Chip Seal); NA means not applicable.

4.4 Factors Affecting Friction Improvement after Preservation

Figures 16 (a) to (e) compare the effective friction numbers after preservation subject to different categories divided by five design factors. The columns indicate the average effective friction number at each site, while the error bars indicate the spread of data within one standard deviation. From the figures, a variety of findings can be observed regarding the effect of design factors on pavement friction. In general, subgrade type and existing pavement condition show less influence on pavement friction compared to the climate and traffic factors. The negative influence of traffic loading on pavement friction can be observed, such as high traffic volume result in lower pavement friction than low traffic volume. However, no consistent trend was observed for the comparison of pavement friction between the regions with different temperature and precipitation conditions.

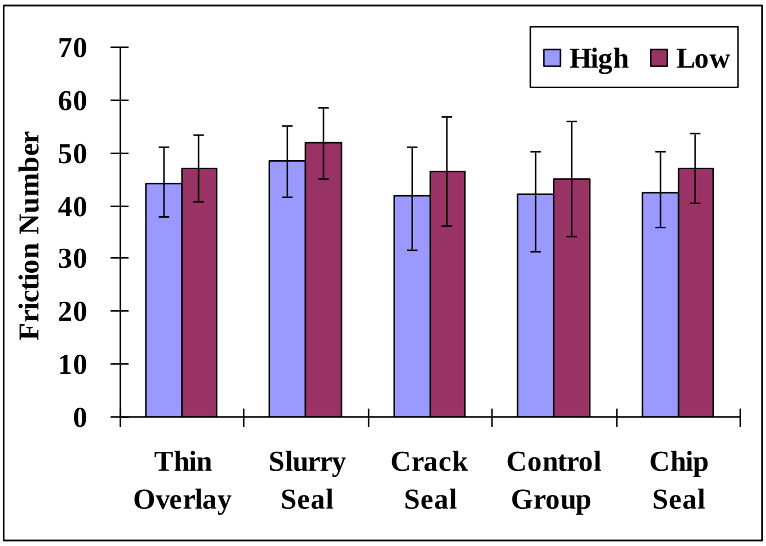


(a)



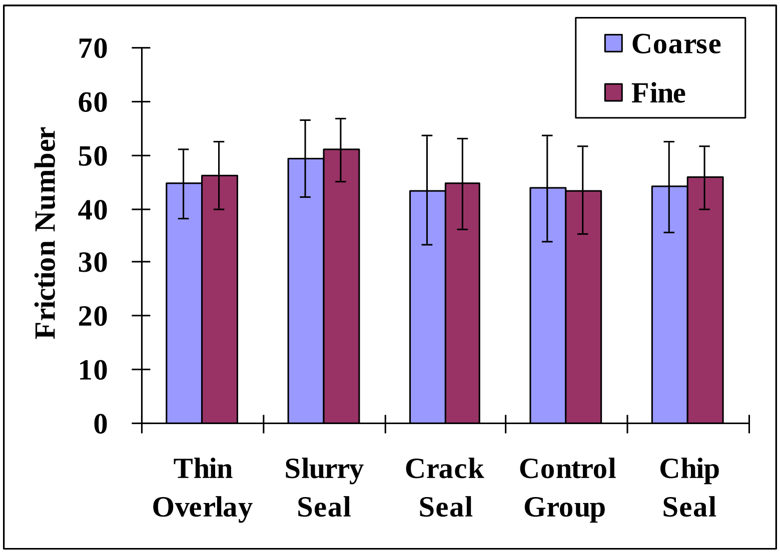
Wet
Dry
Friction Number
70
60
50
40
30
20
10
0
Thin Overlay
Slurry Seal
Crack Seal
Control Group
Chip Seal

(b)



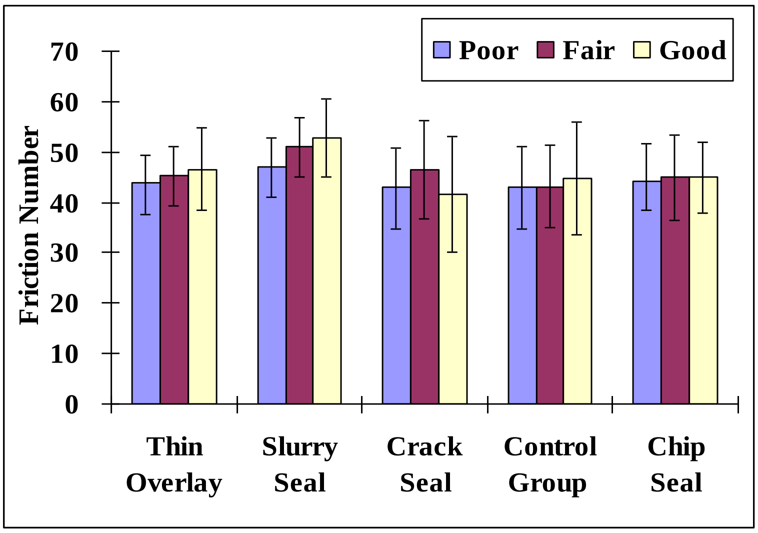
High
Low
Friction Number
70
60
50
40
30
20
10
0
Thin Overlay
Slurry Seal
Crack Seal
Control Group
Chip Seal

(c)



Coarse
Fine
Friction Number
70
60
50
40
30
20
10
0
Thin Overlay
Slurry Seal
Crack Seal
Control Group
Chip Seal

(d)

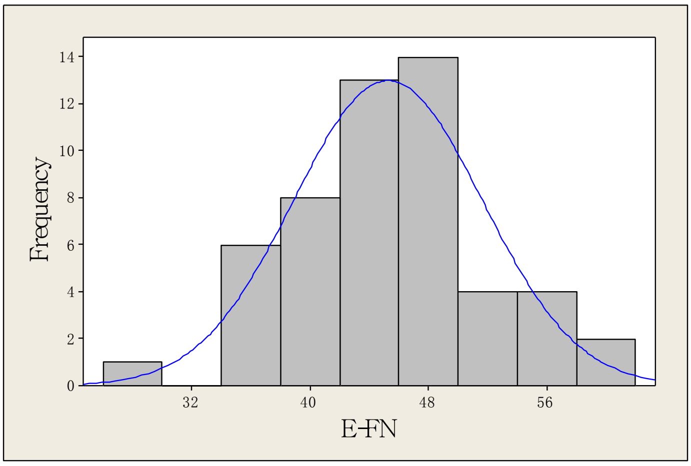


(e)

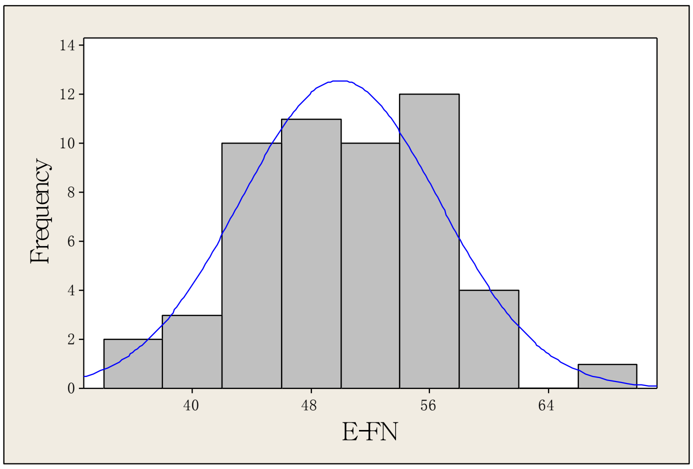
Figure 16 Comparison of E-FN in Each Design Factor for (a) Temperature, (b) Precipitation, (c) Traffic, (d) Subgrade Type, and (e) Pavement Condition

In order to compare the friction improvements caused by different preservation treatments, Fisher's Least Significant Difference (LSD) test was used in the analysis. Fisher’s LSD test belongs to one-way analysis of variance (ANOVA) and its procedure is a two-step testing procedure for pairwise comparisons of several treatment groups. In the first step, a global test is performed for the null hypothesis that the expected means of all treatment groups are equal. If this global null hypothesis can be rejected at the pre-specified level of significance (0.05 in this study), then in the second step, all pairwise comparisons at the same level of significance are performed [50].

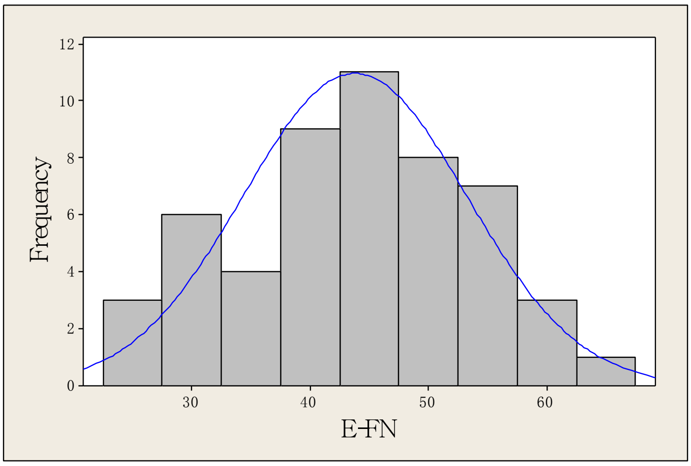
Since the Fisher’s LSD test can only be applied on the data with normal distribution, the examination for the distribution of data is necessary. Figure 17 shows the frequency distributions of the E-FN for each treatment and the control group. The results show that the data are close to normal distribution. For further examination, the Anderson-Darling method is introduced. It is a statistical test to define whether a given sample of data is drawn from a given probability distribution. It is one of the most powerful statistical tools for detecting whether a normal distribution adequately describes a set of data. In the Anderson-Darling method, if the p-value is greater than 0.05, the data is normal distributed. After the analysis, the p-values of the E-FN for thin overlay, slurry seal, crack seal, control group, and chip seal are 0.862, 0.813, 0.503, 0.292, and 0.069, respectively. The results indicate that the all of the data are normally distributed. Subsequently, the Fisher's LSD test is valid for use.



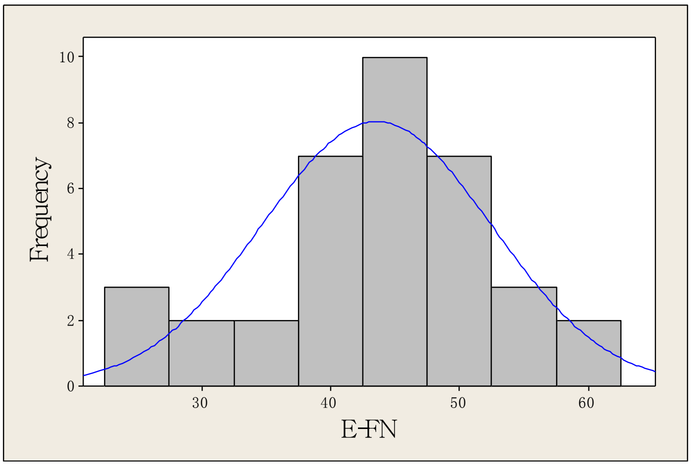
(a)



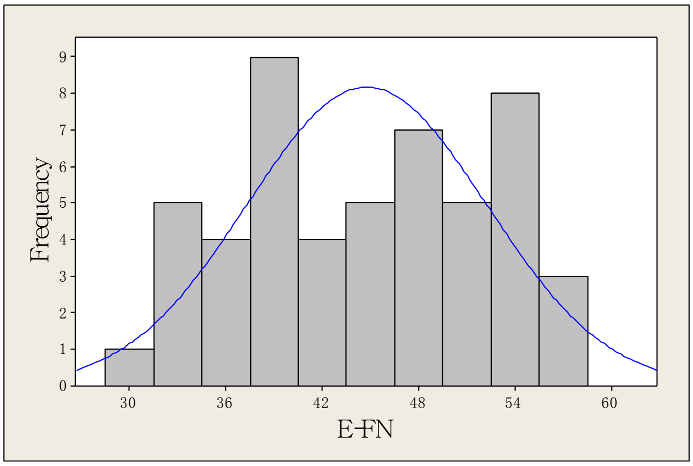
(b)



(c)



(d)



(e)

Figure 17 Frequency Distribution of E-FN for (a) Thin Overlay, (b) Slurry Seal, (c) Crack Seal, (d) Control Group, and (e) Chip Seal

The results after the Fisher's LSD test for all design conditions are summarized in Table 16. To compare the treatments, one of the treatments from the left and another one from the top are selected. If the intersecting cell is empty, there is no significant difference between these two selected treatments; otherwise, the cell is filled with treatment performing better in friction. From the comparison, slurry seal causes significant difference in pavement friction compared to other preservation treatments in the majority of categories. The exceptions are in the sections with freeze condition, coarse grained subgrade and poor pavement condition. As for other three treatments (chip seal, thin overlay and crack seal), only chip seal causes significant difference in pavement friction compared to the control group in the dry region.

Table 16 Fisher LSD Test Results for Various Treatments

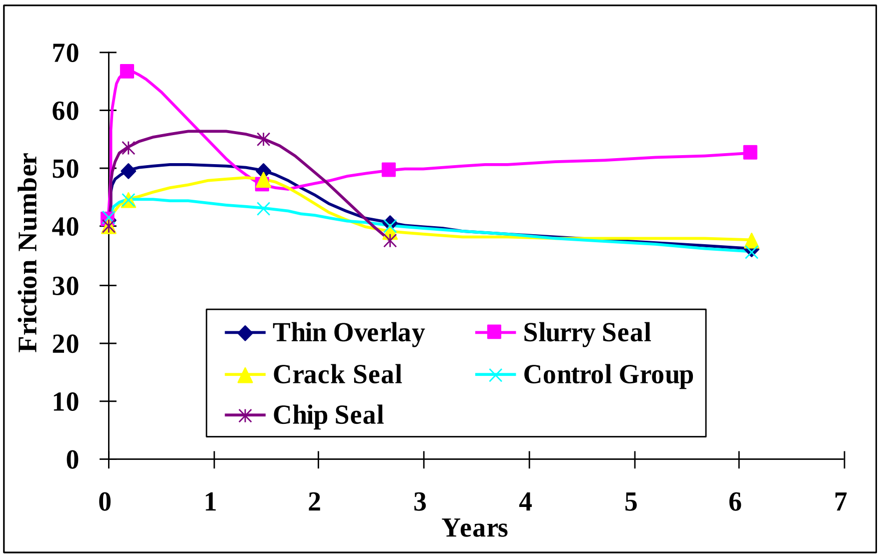
Factor	Level	Treatment	TH	SL	CR	CO
Temperature	Freeze	SL				
		CR				
		CO				
		CH				
	No Freeze	SL	SL			
		CR		SL		
		CO		SL		
		CH		SL		
Precipitation	Wet	SL	SL			
		CR		SL		
		CO		SL		
		CH		SL		
	Dry	SL				
		CR		SL		
		CO		SL		
		CH				CH
Subgrade	Coarse	SL				
		CR				
		CO				
		CH				
	Fine	SL	SL			
		CR		SL		
		CO		SL		
		CH		SL		
Traffic	High	SL	SL			
		CR		SL		
		CO		SL		
		CH		SL		
	Low	SL				
		CR		SL		
		CO		SL		
		CH		SL		
Pavement condition	Poor	**SL**				
		CR				
		CO				
		CH				
	Fair	**SL**	SL			
		CR				
		CO		SL		
		CH		SL		
	Good	**SL**				
		CR		SL		
		CO		SL		
		CH		SL		

*(TH=Thin Overlay, SL=Slurry Seal, CR= Crack Seal, CO= Control, CH=Chip Seal)

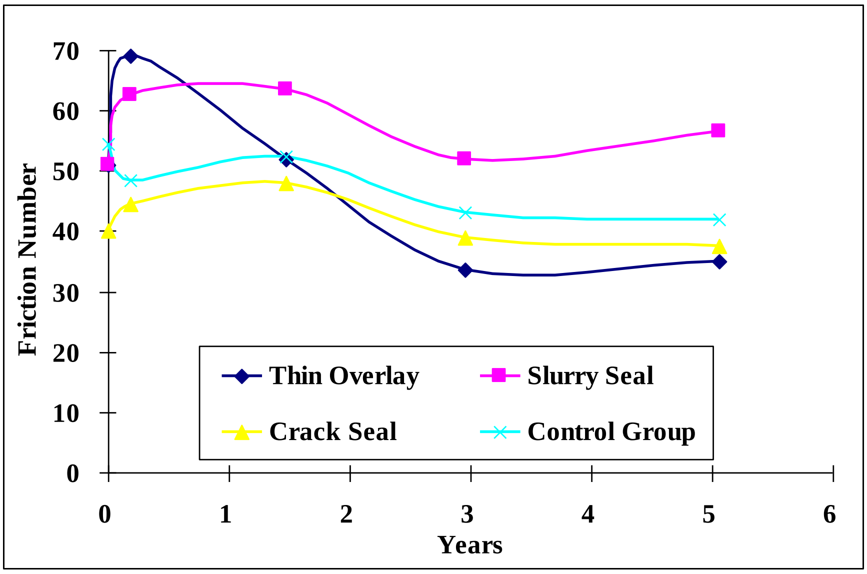
4.5 Regression Models of Friction Variation

Attempts were made to investigate the friction variation with the pavement age.

Figures 18 (a) and (b) show the friction development over the monitoring period at two specific representative sites. It can be observed that although there is a slightly decreasing trend in friction number as the pavement age increases, a large variation in friction was observed. This is probably due to the combined effect of accumulated traffic and climate conditions (such as temperature, precipitation, freeze index, etc.). It is noted that an early-life increase of friction is observed at certain sections. This is probably because that the benefit of aggregate micro-texture may be available sometime after construction when the asphalt coating over the surface aggregate is removed.



(a)



(b)

Figure 18 Friction Variations over the Monitoring Period at (a) TX State Route 19 and (b) TX State Route 105

A multiple regression analysis using a fully stepwise procedure was conducted to consider the effect of traffic and environmental factors on the variation of pavement friction. In the stepwise regression analysis, the first step is to find the variable with the highest coefficient of determination (R-square). In the second step, the variable that would most increase R-square is added if it meets the statistical criterion for entry. The variables that are already included in the model are evaluated, and the variable whose removal would least lower R-square is removed if it meets the statistical criterion for removal. This procedure is repeated until no independent variables that are eligible for entry or removal remain. In this study, the significance level for entry and remaining in the regression model was set as 0.15 [40].

The dependent variable in the regression model is the friction number at each site. The predictor variables considered in the analysis include annually traffic, air temperature, annual average temperature, No.200 sieve passing, No.4 sieve passing, asphalt content, annual precipitation, and freeze index, as shown in Table 14. To better reflect the traffic effect on friction, only the sites having more than four friction measurement points were used in the regression analysis.

Table 17 summarizes the selected variables and the corresponding regression models for the friction number, respectively, for the sections with preservation treatments and the control section. Although the R-square values of the regression models are not high, the results indicate the relatively significant factors that affect the variation of pavement surface friction over the monitoring period. After the stepwise regression, the factors remained in the model are mainly climate and traffic factors. Climate related factors such as freeze index, precipitation, air temperature, and annual average temperature appeared frequently in the model, although the specific factors vary with different preservation treatments.

Generally, precipitation and freeze index show positive influence on the friction number; friction increases as precipitation or freeze index increases. This indicates that temperature should not be the only factor considered that affects the variation of pavement surface friction. As expected, traffic shows certain negative correlation with friction for the section with chip seal and the control section. The insignificance of traffic for the friction variation at other sections could be due to the relatively short monitoring period and the data variation at different measurement locations. On the other hand, pavement surface material property has little influence on the friction variation, which may be due to the small variation of the aggregate type/gradation and asphalt content used in the preservation treatments at different sites.

A similar long-term friction variation model was developed from an earlier study using the data obtained from GPS-1, GPS-2, GPS-6 and GPS-7 in LTPP [51]. The model included vehicle speed, pavement age, cumulative traffic passes, friction test temperature, dry versus wet weather code (dry=1 and wet=0), and freeze versus no freeze weather code (freeze=1 and no freeze=0). Consistent with the models developed in this study, the traffic and climate factors entered into the friction model but the surface material properties were not incorporated. The positive correlation between the precipitation and freeze index and pavement surface friction is consistent for both studies.

It is noted that the R-square in the stepwise regression model is relatively low. There are several reasons. First, the development trend of the friction number seems to follow the nonlinear trend. Though the linear regression model can simplify the result, it may not represent the evolution of friction number accurately. Second, the data from the LTPP database may have some errors. For example, it is hard to find the annual precipitation information for a SPS-3 site. Subsequently, the precipitation is collected from the GPS section near the SPS-3 site. Third, there may be other factors affecting the friction variation that are not considered in the analysis.

Table 17 Stepwise Regression Results of Friction Variation

Treatment Type	Sites	Step	Regression Model	p-value	R-square
Chip Seal	20	1	FN=39.95+0.039FI	0.000	0.13
		2	FN=40.53+0.0454FI-0.023T	0.042	0.16
Crack Seal	24	1	FN=27.93+0.0131P	0.000	0.14
		2	FN=50.75+0.0131P-1.28AT	0.000	0.24
Slurry Seal	23	1	FN=68.41-0.201A	0.000	0.14
		2	FN=61.18-0.196A+0.38AT	0.013	0.16
		3	FN=53.35-0.193A+0.76AT+0.017FI	0.108	0.18
Thin Overlay	18	1	NA	NA	NA
Control	22	1	FN=29.36+0.0123P	0.000	0.13
		2	FN=26+0.0137P+0.041FI	0.000	0.24
		3	FN=26.4+0.014P+0.047FI-0.0028T	0.041	0.27
P=Precipitation (mm), A=Air temperature at the time of testing（°F), T=Traffic (1000 ESAL), FI=Freeze Index, and AT=Annual average temperature (°C)					

It is usually expected that pavement surface friction is mainly affected by traffic-related wear and polishing and climate factors. However, as the pavement deteriorates, the rutting, cracking, raveling at pavement surface may greatly affect the surface texture and influence pavement friction to some extent. Since the International

Roughness Index (IRI) combines the overall pavement distress condition and is widely used by state agencies, stepwise regression analysis was conducted with incorporation of the IRI value. The results show that the influence of roughness on friction is significant in the control section and the section with crack seal. This is reasonable because crack seal contributed less to the pavement distress repair compare to other preservation treatments. The new regression models describing the variation of friction are shown in Equations 4 and 5.

Control Group:

$$FN = 69.87 - 9IRI - 1.09AT - 0.0022T + 0.0045P \quad (R^2 = 0.41) \qquad (4)$$

Crack Seal:

$$FN = 63.66 - 7.3IRI - 1.2AT + 0.0089P \quad (R^2 = 0.31) \qquad (5)$$

The results show that the regression models have relatively high R-Square values when the IRI is considered in the analysis. As the pavement age increases, the pavement surface deterioration will cause an uneven pavement surface, which may decrease pavement surface friction and increase the risk of accidents. The effect of pavement roughness on friction may also be due to the nonlinear relationship between the friction and the dynamic normal load that is induced by the rough road profile during the measurement [52]. This finding would provide better characterization of pavement friction degradation by incorporating pavement roughness into current models. The developed models can be further used to determine the friction requirements for new constructed pavements and the maintenance intervention levels for safety improvement.

4.6 Summary of Findings

This chapter compared the effectiveness of preservation treatments (slurry seal, chip seal, crack seal, and thin overlay) on pavement surface friction and investigated the long-term variation of friction using the data collected in the SPS-3 of the LTPP program. The following findings can be concluded from the analysis:

1. Statistical analysis results (boxplot and Fisher's LSD test) indicate that slurry seal causes significantly greater friction number compared to the control section; and the ranking based on the average friction number among four preservation treatments is: slurry seal, chip seal, thin overlay, and crack seal.
2. Among five design factors in the LTPP program, subgrade type and existing pavement condition show less influence on pavement surface friction compared to the climate (temperature and precipitation) and traffic factors.
3. The stepwise regression analysis establishes the correlation between friction number and the climate and traffic factors. Regression models show that precipitation and freeze index have positive influence on the friction number; friction increases as precipitation or freeze index increases. As expected, traffic shows certain negative correlation with pavement surface friction.
4. It was found that pavement roughness had certain influence on the variation of pavement surface friction for the control sections and the sections with crack seal. This finding would provide better characterization of pavement friction degradation by incorporating pavement roughness into current models.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

Recently, preventive maintenance is receiving significant attention of state DOTs due to the budget constraint on pavement construction and rehabilitation. This study investigated the effectiveness of pavement preservation on mitigating multiple pavement distresses and restoring pavement surface friction using a set of statistical analysis methods. The pavement distresses considered in the analysis include fatigue cracking, longitudinal cracking, transverse cracking, and rutting. The datasets are selected from the SPS-3 of the LTPP program. The SPS-3 includes the performance of four preservation treatments (thin overlay, chip seal, crack seal, and slurry seal) under five design factors (traffic, temperature, precipitation, existing pavement condition, and subgrade type).

The following conclusions were concluded from the analysis:

1. The development trend of fatigue cracking is different from other distresses, such as transverse cracking and rutting. The length of transverse cracks in the pavement is much greater than the length of longitudinal cracks, especially in the sections with chip seal and the control sections.
2. Among the four most prevalent preventive treatments, chip seal and thin overlay both present significant effectiveness in preventing fatigue cracking, longitudinal cracking, and transverse cracking. But thin overlay still outperforms chip seal in rutting resistance.

3. Slurry seal shows significant effectiveness in retarding longitudinal cracking; while crack seal shows significant effectiveness in retarding fatigue cracking.

4. Slurry seal shows great improvement in the pavement surface friction. Rough surface created by cheap seal does not improve the pavement surface friction significantly.

5. Subgrade type and existing pavement condition show less influence on pavement surface friction compared to the climate (temperature and precipitation) and traffic factors.

6. Pavement roughness had certain influence on the variation of pavement surface friction for the control sections and the sections with crack seal.

5.2 Future Research Recommendations

The following research recommendations were concluded from this study:

1. The proper timing of applying pavement preservation can significantly extend the service life of pavement. However, this effect is not considered in this study and need to be investigated in the future study.

2. In many cases, several candidate preservation treatments show the effectiveness to retard the pavement deterioration. To select the most cost-effective preservation treatment, the life cycle cost of the pavement should be considered.

3. The method of mechanistic-empirical pavement design can be used to analyze the performance of pavement preservation in the future study and provide more meaningful results.

4. The linear regression model was used in this study to model the long-term variation of pavement surface friction. Nonlinear regression models should be considered in the further study to improve the model accuracy.

5. The factors that affect the effectiveness of treatments in the presented study include existing pavement condition, traffic level, temperature, and precipitation. Other potential significant variables including pavement structural and surface material properties are recommended to be investigated.

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