Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development of Decision Trees for the Selection of Pavement Maintenance and Rehabilitation Activities in South-Central United States

Project No. 20PLSU02

Lead University: Louisiana State University

Final Report
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Disclaimer

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16. Abstract

Over time, new pavements deteriorate under the combined effects of traffic loading and the environment, no matter how well-designed or constructed. In general, maintenance and rehabilitation activities are employed to slow down or reset the rate of pavement deterioration. Cement-Stabilized Full Depth Reclamation (CSFDR) is a common rehabilitation treatment used by transportation agencies, specifically in Louisiana. Likewise, Ultra-Thin overlay (UTO) is a pavement maintenance treatment that has increased in popularity in recent years in Region 6. Yet, several gaps exist in the literature regarding the long-term field performance and cost-effectiveness of these two treatments especially in hot and humid climates. Therefore, the key objectives of this study were to assess the immediate benefits and long-term field performance as well as the cost-effectiveness of these two treatments in Louisiana. To achieve these objectives, numerous CSFDR and UTO projects were identified from the Louisiana Department of Transportation (LaDOTD) Pavement Management System (PMS) database and analyzed in terms of alligator cracks, rutting, random cracks, and roughness over a monitoring period of up to 15 years. Results indicated that the performance of CSFDR is significantly affected by the pre-treatment pavement conditions, applied overlay thickness, and traffic. Results also indicated that CSFDR projects would usually fail due to the development of random cracks. This could be attributed to the development of shrinkage cracks, which is a common problem with cement stabilization in Louisiana. A regression model was developed to predict the service life of CSFDR based on project conditions. Results also showed that UTO considerably extended the Pavement Service Life (PSL) for all the distress indices. This extension varied based on the pre-treatment pavement conditions and traffic level. As such, a predictive model was developed, with reasonable accuracy, to predict the extension in PSL of UTO based on project conditions. The developed models in this project for CSFDR and UTO will help state agencies make effective decisions for the maintenance and rehabilitation of their pavements.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m	square meters	10.764	square feet	ft^2
m	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m	cubic meters	35.314	cubic feet	ft^3
m	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CSFDR	Cement-Stabilized Full Depth Reclamation
LaDOTD	Louisiana Department of Transportation and Development
SFDR	Stabilized Full Depth Reclamation
RAP	Reclaimed Asphalt Pavement
FWD	Falling Weight Deflectometer
R^2	Coefficient of Determination
ME	Mechanistic Empirical
CSD	Cement Stabilized Design
CTD	Cement Treated Design
UTO	Ultra-Thin overlay
PCI	Pavement Condition Index
RNDM	Random Cracking Index
RUFF	Roughness Index
RUT	Rutting Index
ALCR	Alligator Cracking Index

EXECUTIVE SUMMARY

Over time, new pavements deteriorate under the combined effects of traffic loading and the environment, no matter how well-designed or constructed. In general, maintenance and rehabilitation activities are employed to slow down or reset the rate of pavement deterioration. Rehabilitation activities are those activities conducted to repair portions of an existing pavement to reset the deterioration rate. They are defined by the American Association of State Highway and Transportation Officials (AASHTO) as "structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity *(1)*." On the other hand, maintenance activities are used by transportation agencies to reduce the rate of deterioration of existing pavements through identifying and addressing specific pavement deficiencies that contribute to overall deterioration. Maintenance activities are commonly included in pavement preservation programs, which are defined by the Federal Highway Administration (FHWA) as "a program of activities aimed at preserving investment in the Nation's highway system, providing and maintaining serviceable roadways, extending pavement life, enhancing pavement performance, ensuring cost effectiveness, and reducing user delays—in short, meeting customers' needs. This includes corrective maintenance and preventive maintenance, as well as minor rehabilitation projects. However, it excludes new or reconstructed pavements and pavements requiring major rehabilitation *(2)*."

Cement-Stabilized Full Depth Reclamation (CSFDR) is a common rehabilitation treatment used by transportation agencies, specifically in Louisiana. Likewise, Ultra-Thin overlay (UTO) is a pavement maintenance treatment that has increased in popularity in recent years in Region 6. Yet, several gaps exist in the literature regarding the long-term field performance and cost-effectiveness of these two treatments especially in hot and humid climates. Therefore, the key objectives of this study were to assess the immediate benefits and long-term field performance as well as the cost-effectiveness of these two treatments in Louisiana. To achieve these objectives, numerous CSFDR and UTO projects were identified from the Louisiana Department of Transportation (LaDOTD) Pavement Management System (PMS) database and analyzed in terms of alligator cracks, rutting, random cracks, and roughness over a monitoring period of up to 15 years.

Results indicated that the performance of CSFDR is significantly affected by the pre-treatment pavement conditions, applied overlay thickness, and traffic. Results also indicated that CSFDR projects would usually fail due to the development of random cracks. This could be attributed to the development of shrinkage cracks, which is a common problem with cement stabilization in Louisiana. A regression model was developed to predict the service life of CSFDR based on project conditions. Results also showed that UTO considerably extended the Pavement Service Life (PSL) for all the distress indices. This extension varied based on the pre-treatment pavement conditions and traffic level. As such, a predictive model was developed, with reasonable accuracy, to predict the extension in PSL of UTO based on project conditions. The developed models in this project for CSFDR and UTO will help state agencies make effective decisions for the maintenance and rehabilitation of their pavements.

1. INTRODUCTION

Over time, new pavements deteriorate under the combined effects of traffic loading and the environment, no matter how well-designed or constructed. In general, maintenance and rehabilitation activities are employed to slow down or reset the rate of pavement deterioration. Stabilized Full Depth Reclamation (SFDR) is a common rehabilitation treatment used by transportation agencies. This rehabilitation treatment involves (i) cold planning of all or most of the asphalt surface, (ii) blending the pulverized/ reclaimed material with underlying aggregate and add a stabilization additive to produce a homogeneous base material, and (iii) placing a new asphalt overlay *(3)*. Generally, base stabilization enhances the pavement structure by improving its rutting resistance, stiffness, durability, and fatigue resistance as well as overcoming grade change restrictions *(4)*.

For more than 50 years, the Louisiana Department of Transportation and Development (LaDOTD) has used Portland cement for subgrade stabilization in asphalt pavement *(5)*. In general, soil cement is a composite material of pulverized soil, Portland cement, and water, which forms a durable and strong structural material *(6)*. This type of base course, although known for having an excellent loading carrying capacity and durability, is also well-known for developing shrinkage cracks, which can reflect through the asphalt surface and accelerate pavement deterioration *(7)*.

The design and construction processes for SFDR have been well researched and documented in previous studies *(8, 9)*. In addition, several studies have documented the benefits of base stabilization through laboratory testing *(10)*. Other studies documented the immediate benefits of base stabilization in the field in terms of increased pavement structural capacity *(6)*. Yet, fewer studies quantified the impact of these immediate benefits (improved pavement structural condition) on the long-term field performance of asphalt pavements, particularly in hot and humid climates such as Louisiana. Due to this shortcoming, the literature also lacks studies evaluating the cost-effectiveness of this type of treatment considering its long-term field performance. Therefore, there is an important need to evaluate the long-term field performance; in terms of service life, and cost-effectiveness of cement-stabilized full depth reclamation (CSFDR) to identify pavement failure and subsequently plan for future rehabilitation activities. This is a critical issue for many states as overestimation or underestimation of pavement service life affect maintenance and rehabilitation decisions, pavement type's selection, and may result in inadequate allocation of maintenance and rehabilitation funds.

Likewise, Ultra-Thin Hot-Mix Asphalt Overlay (UTO) is a maintenance treatment that is growing in popularity among transportation agencies is *(11)*. UTO is a high-performance surface course applied over either asphalt or concrete pavements. It is a one-pass construction process that consists of a heavy application of polymer-modified asphalt emulsion membrane followed by an ultra-thin gap-graded hot-mix asphalt (HMA), both placed by a single machine. The thick polymer membrane seals and protects the surface and provides superior bonding of the ultra-thin mix to the pavement *(12)*. Typically, the thickness of this treatment ranges between 9.5 mm (3/8 inch) and 25.4 mm (1 inch) *(13)*. Previous studies indicated that UTO successfully (a) improved skid resistance, (b) reduced noise, (c) minimized back spray, (d) enhanced surface sealing, (e) improved wheel rutting, and (f) increased visibility under wet conditions *(14, 15)*.

UTO has received considerable interest in Louisiana in recent years. As of 2016, 50% of the districts in Louisiana indicated using UTO as a maintenance treatment. While the selection and construction processes for UTO has been well researched and documented in previous studies *(16)*, few studies were conducted to assess the field performance and cost-effectiveness of UTO especially in hot and wet climates such as Louisiana. Therefore, factors that may affect the field performance of UTO should be evaluated and quantified to ensure that this treatment is only used when positive benefits are expected. This would also allow quantifying the cost-effectiveness of this treatment method in extending the pavement service life.

2. OBJECTIVES

The primary objective of this project was to develop decision trees or models that could help state agencies select pavement maintenance and rehabilitation activities in South-Central United States. In specific, this study aimed to:

- Assess the immediate benefits and long-term field performance of CSFDR treatments in Louisiana.
- Evaluate the cost-effectiveness of CSFDR treatments in Louisiana.
- Develop a regression model that could predict the long-term benefits of CSFDR treatments in hot and humid climates based on the project conditions.
- Assess the immediate benefits of UTO treatments in hot and humid climates.
- Evaluate the long-term field performance of UTO treatments in hot and humid climates.
- Develop a predictive model that could estimate the long-term field performance of UTO treatments in hot and humid climates.
- Investigate the cost-effectiveness of UTO treatments in hot and humid climates.

3. LITERATURE REVIEW

3.1. Cement-Stabilized Bases

3.1.1 Louisiana Current Practice in Using Cement-Stabilized Bases

In Louisiana, in-place cement stabilization of base courses is governed by Section 303 of the Louisiana Standard Specifications for Roads and Bridges. In general, two types of soil cement base designs are used in Louisiana. This includes cement stabilized design (CSD) and cement treated design (CTD). CSD refers to a 216 mm (8.5 in)-thick soil cement design with a high cement content (minimum 8%) to achieve a 7-day compressive strength of 2.1×10^6 N/m^2 (300 psi), while CTD refers to a 305 mm (12 in)-thick soil cement design with a low cement content (4-6%) to obtain a minimum 7-day compressive strength of 1.0×10^6 N/m^2 (150 psi) *(6).*

In Louisiana, "trigger values" are used to decide on rehabilitation actions, including CSFDR. Trigger values are threshold distress indices established by LaDOTD to determine a certain type of rehabilitation action. These values differ based on the treatment type, road functional class, and pavement type. For example, if the alligator cracking index on a collector flexible pavement drops below 60, LaDOTD selects "In-place stabilization." Once a trigger value is reached, the selected treatment is added to a list of pending projects prepared by LaDOTD. Then, LaDOTD evaluates the cost-effectiveness of these projects to determine the order in which these projects are to be executed. The final list prepared by LaDOTD is then reviewed by each district separately, where the recommended treatments are evaluated and approved by each district based on core extraction (if needed). The list of district-approved treatments is eventually sent back to LaDOTD for final approval.

3.1.2 Performance of Cement-Stabilized Bases

In 2002, Taha et al. *(17)* conducted a laboratory evaluation of cement-stabilized reclaimed asphalt pavement (RAP)-virgin aggregate blends as base materials. The blends were prepared using 0, 3, 5, and 7% Type I Portland cement (by dry weight of the aggregate) with 100/0, 90/10, 80/20, 70/30, and 0/100% RAP to virgin aggregates. Compaction and unconfined compressive strength tests were performed on the blends. As expected, the results indicated that as the cement content in the blend increased, the strength value increased resulting in a slightly lower required base thickness. Results also indicated that 100% RAP aggregate could be successfully utilized as a conventional base material if stabilized with cement. Similarly, other studies highlighted the potential benefits of cement-stabilized bases through laboratory testing *(10).*

In addition to laboratory testing, research studies evaluated the field performance of cement-stabilized bases. In 2017, François *(18)* evaluated the impact of base stabilization on the fatigue and rutting performance of flexible pavements in Rhode Island. A total of five test sections were considered in this study. One of the five sections was constructed as a control section using an untreated Reclaimed Asphalt Pavement (RAP) aggregates base, while the remaining four sections were constructed using stabilized base layers. The four stabilizing agents were calcium chloride, emulsified asphalt, Portland cement, and geogrid. Falling Weight Deflectometer (FWD) tests were conducted on all the sections and the collected data were used to backcalculate the elastic moduli for all the layers. The backcalculated moduli were then used in a Mechanistic Empirical (ME) pavement analysis. Based on the findings, it was concluded that cement-stabilized base was the most effective option in improving the fatigue cracking resistance of asphalt pavements. It was also concluded that base stabilization had little effect on improving the rutting resistance of asphalt pavements.

In 2019, Jones et al. *(19)* conducted an accelerated loading test in California to compare between full-depth reclamation with Portland cement and full-depth reclamation without a stabilizer. Results indicated that after testing, the section with cement-stabilized base exhibited significantly lower permanent deformation than the section with non-stabilized base. Furthermore, no cracking was observed on either section after testing. In 2019, Eugene et al. *(20)* evaluated the eight-year field performance of three full-depth reclamation projects. In these projects, the stabilizing agents were foamed asphalt (2.7% with 1% cement), asphalt emulsion (3.5%), and Portland cement (5%). The performance of these projects was evaluated in terms of rutting, fatigue cracking, transverse cracking, and International Roughness Index (IRI). In general, results indicated that the three full-depth reclamation projects performed better than the non-stabilized sections. It was also concluded that roughness was improved for the cement-stabilized sections compared to the asphalt-stabilized sections.

3.2. Ultra-Thin Overlay

3.2.1 Louisiana Current Practice in Using Ultra-Thin Overlay

To decide which rehabilitation or maintenance treatment to apply in road sections in Louisiana, the Louisiana department of Transportation and Development (LaDOTD) undertakes a systematic process that consists of trigger values. Trigger values are threshold values that were assigned by LaDOTD to each independent treatment type, based on the corresponding distress indices, existing pavement surface type, and road functional class. When a treatment's trigger value is reached for a specific road section, the treatment is automatically assigned to that particular section and added to LaDOTD's list of pending projects. Afterwards, projects in this list are prioritized based on a cost-benefit analysis, to determine when these projects will be executed. The prioritized list is then sent to all districts for review at a project level, where they decide if they adopt the recommendations made by LaDOTD, or select alternative treatments with a corresponding technical justification. Once reviewed, the list is sent back to LaDOTD for final approval. Up to date, there are no trigger values assigned for UTO by LaDOTD. For this reason, districts in Louisiana consider UTO as an intermediate alternative between thin asphalt overlays and microsurfacing. As such, districts select UTO for a specific road when the selected treatment by LaDOTD is either microsurfacing or thin asphalt overlay.

3.2.2 Performance of Ultra-Thin Overlay

Several studies have been conducted to evaluate the field performance of UTO. In 2000, the Minnesota Department of Transportation (MnDOT) constructed two equivalent UTO sections on two reference posts of US-169 *(21)*. The original pavement included transverse cracks that were sealed before the application of the UTO treatment. A third section without UTO treatment, where the cracks were sealed and potholes patched, was designated as the control section. The performance of the two UTO sections and the control section was evaluated over a seven-year monitoring period in terms of ride quality, transverse cracking, and edge damage. Visual inspections were performed on the UTO sections and the control section to assess their condition. Results indicated that the average ride quality index (RQI) of the UTO section after seven years was 3.2, while the control section had an average RQI of 1.9 (below the rehabilitation trigger value of 2.5). Results also indicated that no weathering or edge deterioration was observed on the UTO sections. It was concluded in this study that the treated sections would not reach the rehabilitation trigger value for another five years after the inspection, while the control section required major rehabilitation.

In 2001, UTO was placed on a road section in Washington *(22).* The performance of this treatment was evaluated during a period of six years by Washington State Department of Transportation through pavement condition surveys and visual inspections. Results showed that the UTO was effective in reducing the frequency and severity of cracking. Results also indicated that after application of the UTO, rutting was minimized, and ride quality was improved and remained adequate throughout the evaluation period.

In 2004, a research study was conducted in Louisiana to assess the field performance of UTO projects in Louisiana *(23).* Two UTO projects located in Lafourche Parish were selected and evaluated in terms of rutting, alligator cracking, random cracking, transverse cracking, and roughness over a period of six years. A life-cycle cost analysis was also performed to compare the cost effectiveness of the two UTO project to two other mill and overlay projects used as control sections. Results showed that the two UTO projects performed better than the control sections in terms of roughness, rutting, and longitudinal, transverse, and random cracking. It was reported in this study that the expected service life of UTO was about 10 years. Results from the life-cycle cost analysis showed that the UTO projects had a life-cycle cost of $7.34/yd2, resulting in cost savings of approximately $3.34/yd2 for LaDOTD when compared to the conventional mill and overlay control sections.

In 2014, a research study was conducted to evaluate the field performance of UTO projects in Kansas using distress data from the Pavement Management Information System *(24).* Results indicated that UTO projects had a high variability in service life with most of the projects having a service life of about six years. Results from the before and after analysis indicated that UTO reduced pavement roughness, transverse, and fatigue cracking one year after UTO application. UTO proved to be less effective in alleviating transverse and fatigue cracking after a few years in service. In 2015, three UTO field projects were evaluated in Beaumont, Odessa, and Paris districts of Texas *(25).* The field performance was evaluated in terms of the International Roughness Index (IRI) and Skid Number. Results indicated that UTO showed a superior performance after five years, with excellent skid and crack resistance. Results also showed that after UTO application, IRI was typically reduced by 35 to 50% and the typical range for the skid number was between 30 and 50. A comparison between the costs of UTO (25 mm thick) and conventional HMA overlay (50 mm thick) was also conducted. It was concluded that in average, UTO costs were approximately 30% less than conventional HMA overlays.

4. Data Collection

In Louisiana, maintenance and rehabilitation activities are monitored via the LaDOTD PMS databases. Pavement performance data are reported in LaDOTD PMS for the period ranging from 1996 to 2019. These data are based on pavement condition measurements that are collected biennially using the Automatic Road Analyzer (ARAN®) system that provides a continuous assessment of the road network. Video crack surveys are available for each state highway in Louisiana and were reviewed using VisiData™ software *(26, 27)*.

Collected data are reported every 1/10th of a mile and are analyzed to calculate different distress indices on a scale from zero to 100 (100 being perfect conditions). These indices include the Pavement Condition Index (PCI), Alligator Cracking Index (ALCR), Rutting Index (RUT), Random Cracking Index (RNDM), Roughness Index (RUFF), and Patch Index (PTCH). For flexible pavements, the PCI is calculated as follows *(26, 27):*

$$\text{PCI} = \text{MAX}\,[\text{MIN}\,(\text{RNDM, ALCR, PTCH, RUFF, RUT}), \{\text{AVG}\,(\text{RNDM, ALCR, PTCH, RUFF, RUT}) - 0.85 \text{ standard deviation}\,(\text{RNDM, ALCR, PTCH, RUFF, RUT})\}] \quad (1)$$

Alligator Cracking Index (ALCR) reflects the extent (in terms of crack area) and severity of alligator cracks existing on the pavement surface, while the Random Cracking Index (RNDM) reflects the extent (in terms of crack length) and severity of random cracks existing on the pavement surface including thermal transverse, reflective transverse, longitudinal, block, and cement-treated reflective cracks. ALCR or RNDM are calculated as follows *(26, 27)*:

$$\text{X} = \text{Maximum of 0 and } (100 - DP_L - DP_M - DP_H) \quad (2)$$

$$\text{ALCR or RNDM} = \text{Minimum of 100 and X} \quad (3)$$

where,

DP = deduct point due to alligator cracks or random cracks; and subscripts L, M, and H refer to the low, medium, and high severity of the cracks, respectively. The Roughness Index (RUFF) reflects the irregularities in the pavement surface and is expressed on a scale from zero to 100 with 100 representing the case of a smooth pavement. It is related to the IRI using the following empirical equation *(26, 27):*

$$\text{IRI (in/mile)} = (100 - \text{RI}) \times 5 + 50 \quad (4)$$

The Rutting Index (RUT) reflects the average rutting depth (R_AVG) in the pavement surface, and is expressed in a scale from 0 to 100 with 100 representing the case with no rutting. This index is calculated as follows:

$$\text{If } (\text{R\_AVG}>=0 \text{ mm and R\_AVG}<3.1 \text{ mm}), \text{ then RUT}=100 \quad (5)$$

$$\text{If } (\text{R\_AVG}>=3.1 \text{ mm and R\_AVG}<35 \text{ mm}), \text{ then RUT}=-80\times (\text{R\_AVG [in inch]}) +110 \quad (6)$$

$$\text{If } (\text{R\_AVG}>=35 \text{ mm}), \text{ then RUT}=0 \quad (7)$$

In this project, two groups of data were mined from LaDOTD PMS database, group 1 for Cement-Stabilized Bases and group 2 for UTO. Each group consisted of five datasets as described in the following subsections.

4.1. Group 1

To create this group, LaDOTD databases were mined to identify all CSFDR projects in Louisiana. In total, 122 CSFDR projects were identified. For all of these projects, the ALCR, RNDM, RUFF, and RUT were collected before and after treatment application to determine the PSL in terms of these distresses. For any project to be included in the analysis, it had to meet all the following acceptance criteria:

- A project has one index before the treatment application
- A project has at least three indices after the treatment application
- A project exhibits condition improvement immediately after treatment application
- A project exhibits condition deterioration along the treatment service life, which is indicative that no other treatments were applied during the analysis period.

Table 1 presents the number of projects considered in each dataset. In addition to the collected indices, additional data were collected including the control section number, log mile (beginning and end), treatment application date, applied overlay thickness (t), and Average Daily Traffic (ADT).

Table 1. Datasets in Group 1

Dataset Number	Analysis	Number of Projects
1	Overall analysis	122
2	Alligator Cracking Analysis	110
3	Rutting Analysis	96
4	Roughness Analysis	70
5	Random Cracking Analysis	106

4.2. Group 2

To create this group, a total of eight UTO projects were identified from LaDOTD databases. To provide an accurate presentation of the effect of UTO application, the analysis of these projects was conducted for every log-mile (0.1 mile), which was considered as a single data point. For every log-mile within the eight UTO projects, the PCI values were collected before and after UTO application over a monitoring period of 14 years (6 years before UTO application and 8 years after UTO application). For any log-mile to be included in the final analysis, it had to meet all the following quality criteria:

- The log-mile has at least three PCI values before UTO application
- The log-mile has at least four PCI values after UTO application
- The first PCI after UTO application should exhibit significant increase to confirm that UTO was applied

- The PCI values collected before and after UTO application should follow a decreasing trend indicating that no further maintenance or rehabilitation treatments were applied during the 14-year monitoring period.

A total of 126 log-miles included in seven pavement sections fulfilled the aforementioned criteria and were considered in the analysis. For the selected 126 log-miles, additional data were collected including the Average Daily Truck Traffic (ADTT), UTO unit cost ($/lane-mile), and road functional class (FS). Additionally, the ALCR, RUT, RNDM and RUFF were collected before and after UTO application when available. Table 2 presents the datasets included in Group 2.

Table 2. Datasets in Group 2

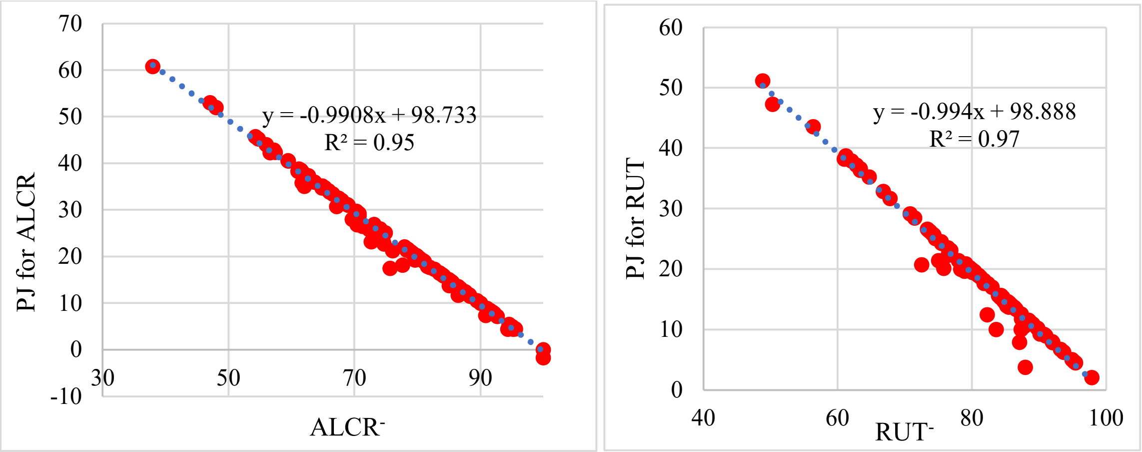
Dataset ID	Collected Index	Number of Projects	Number of Data Points (Log-miles)
6	PCI	7	126
7	RUFF	7	112
8	RNDM	7	111
9	ALCR	7	96
10	RUT	7	106

5. Analysis and Findings

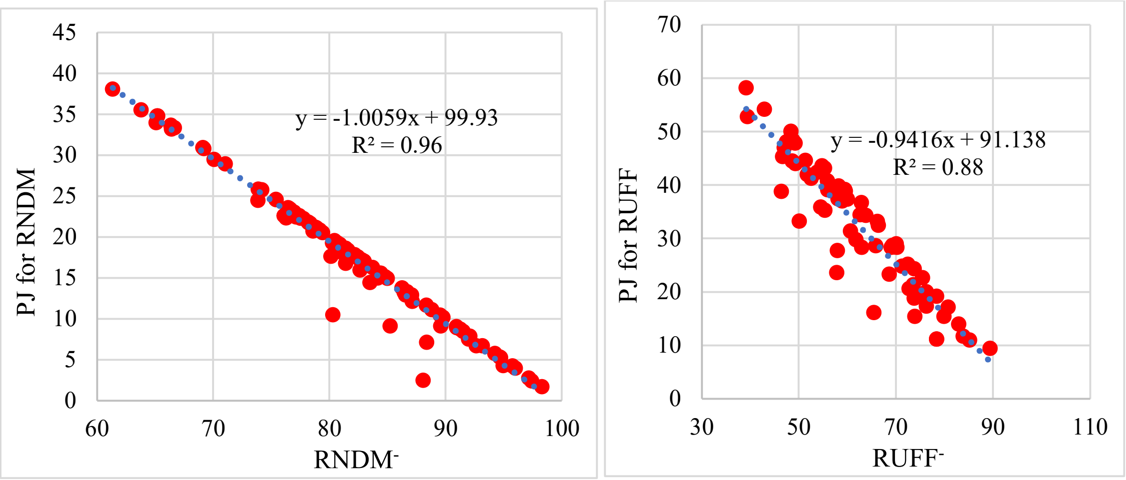
5.1. Cement-Stabilized Bases

5.1.1 Immediate Benefits

Throughout this project, the terms PCI$^-$, ALCR$^-$, RNDM$^-$, RUFF$^-$, and RUT$^-$ would refer to the distress index prior to treatment application for PCI, ALCR, RNDM, RUFFI, and RUT, respectively. The immediate benefit of CSFDR projects was evaluated in terms of Performance Jump (PJ), which was calculated for every project and for every distress index. Datasets 2, 3, 4 and 5, shown in Table 1, were utilized to calculate the PJ for every CSFDR project by subtracting the pre-treatment index from the first collected index after treatment. Figure 1 shows the PJ for all the CSFDR projects for the different indices. As expected, all the CSFDR projects had positive PJ for all the indices. While it is expected that all indices jump after CSFDR application, not all the indices jump to 100. Therefore, Figure 1 presents simple regression models with superior accuracy that could be used to predict the PJ for the different distresses based on the pre-treatment pavement conditions. This is useful in PMS in order to quantify the immediate restoration of the distress indices after CSFDR application. Based on the results of this section, it was concluded that CSFDR had a significant immediate effect on ALCR, RNDM, RUFF, and RUT indicating that it significantly corrected all pre-existing pavement deficiencies. Therefore, the analysis in the following sections considered these four distresses to quantify the long-term field benefits of CSFDR.



(a) (b)



(c) (d)

Figure 1 Correlation between Performance Jump and pre-treatment pavement conditions for (a) ALCR, (b) RUT, (c) RNDM, and (d) RUFF

5.1.2 Long-Term Benefits

The long-term field benefits of CSFDR were assessed in terms of PSL after treatment application. Using Datasets 2, 3, 4, and 5, alligator cracking, rutting, random cracking, and roughness performance curves were developed for each project, respectively, with the collected indices plotted against age. Indices exactly at the treatment application date, which corresponds to year zero, were extrapolated using the collected indices after treatment application. Quadratic polynomial models provided the best fit in most cases. Using the fitted models, the PSL was calculated as the number of years to reach a threshold index value, see Figure 2. A threshold index of 60 was used for all the distresses to match the trigger values used by LaDOTD. Throughout this project, the subscript i represents the distress type. For example, PSL$_{ALCR}$ represents the PSL of a specific project based on the measured alligator cracking indices.

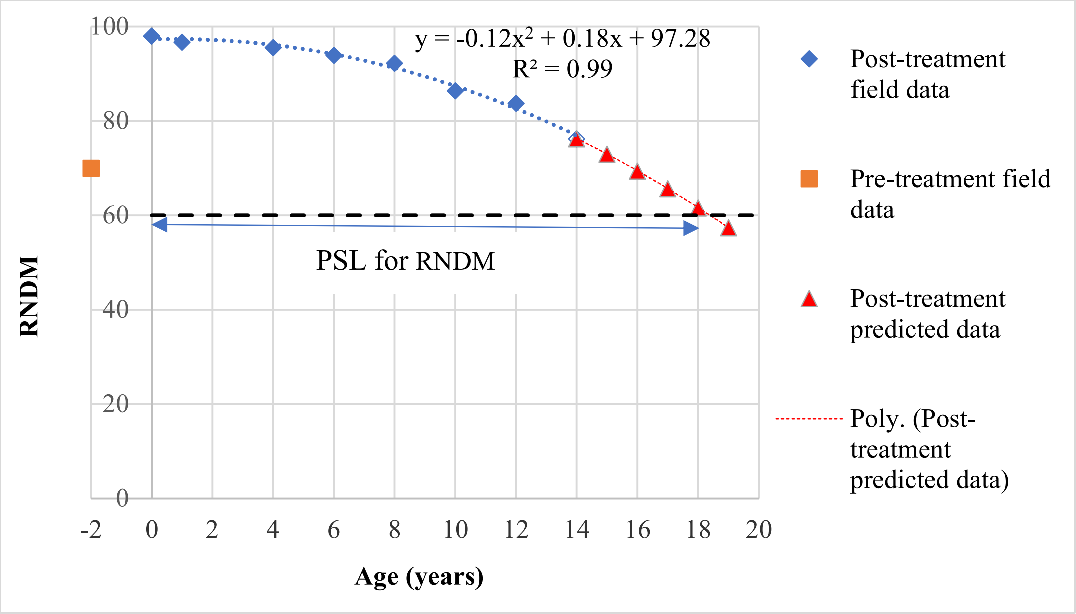


Figure 2 Calculation of PSL (in terms of RNDM) for one project (as an example) over 14 Years Monitoring Period

Fatigue Analysis

Dataset 2 in Table 1 was used to calculate PSL_{ALCR} for all the CSFDR projects using the relevant project performance parameters and unit costs. Since the pre-treatment pavement conditions significantly affect the long-term field performance of maintenance and rehabilitation treatments *(28)*, the calculated PSL_{ALCR} were grouped based on the $ALCR^-$. The pre-treatment groups were: <60, 60-70, 70-80, 80-90, and 90-100. Eventually, the average PSL_{ALCR} was computed for every $ALCR^-$ group, see Figure 3. Based on Figure 3, the average PSL varied between 24 and 38 years depending on the pre-treatment pavement conditions. It should be noted that these values may be considered as conceptual values and not the actual pavement service life, since they are based only on alligator cracking without considering other distresses, which would cause earlier pavement failure. The actual service life considering all distresses is presented in the following sections.

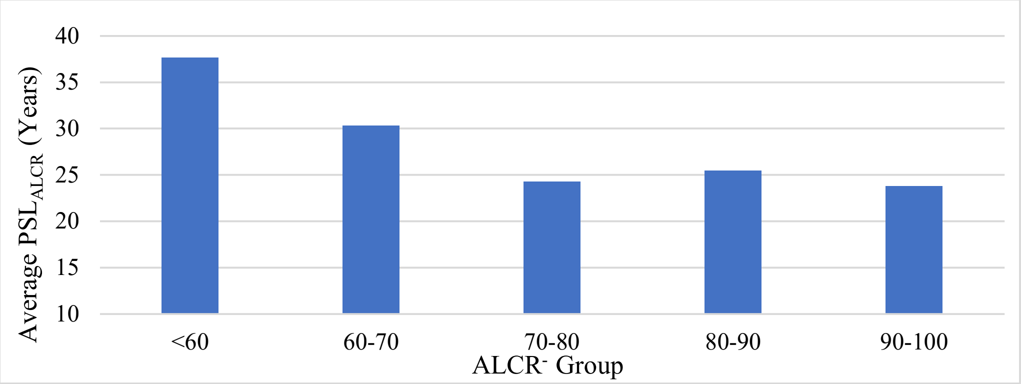


Fig. 3. Average PSL_{ALCR} for the CSFDR projects at different $ALCR^-$ groups

Rutting Analysis

Similarly, a rutting analysis was conducted using Dataset 3 in Table 1 to evaluate the long-term rutting performance of CSFDR projects. Figure 4 presents the average PSL_{RUT} for the CSFDR projects for different RUT^- groups. Based on Figure 4, the average PSL varied between 24 and 28 years according to the pre-treatment pavement conditions.

Roughness Analysis

A roughness analysis was conducted using Dataset 4 in Table 1 to evaluate the long-term field performance of CSFDR projects in terms of roughness. Figure 5 shows the average PSL_{RUFF} for the CSFDR projects at different $RUFF^-$ groups. According to Figure 5, the average PSL varied between 31 and 33 years according to $RUFF^-$. These relatively high values (when compared to the average PSL_{ALCR} and PSL_{RUT}) indicate that CSFDR is more effective in improving the roughness of asphalt pavements than improving the fatigue and rutting performances. This agrees with previous studies, which indicated that cement-stabilized sections had superior roughness performance *(20)*.

Random Cracking Analysis

A random cracking analysis was conducted using Dataset 5 in Table 1 to evaluate the long-term cracking performance of CSFDR. Figure 6 presents the average PSL_{RNDM} for the CSFDR projects at different RNDM$^-$ groups. As shown, the average PSL varied between 21 and 25 years according to the pre-treatment pavement conditions. It is worth noting that these values were less than the PSL for alligator cracking, rutting, and roughness. This suggests that CSFDR projects would usually fail due to the development of random cracks. This could be attributed to the development of shrinkage cracks, which is a common problem with cement stabilization in Louisiana. These cracks can reflect through the asphalt surface in a short period of time and accelerate pavement deterioration.

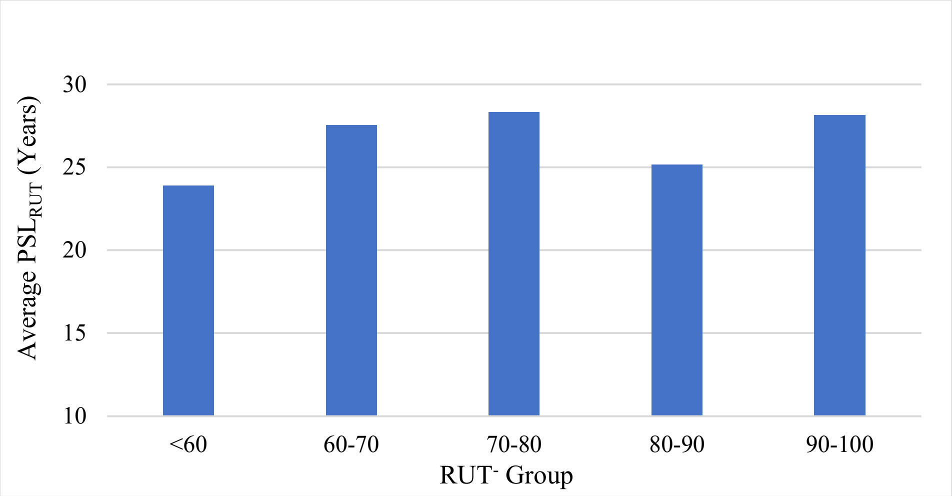


Fig. 4. Average PSL$_{RUT}$ for the CSFDR projects at different RUT$^-$ groups

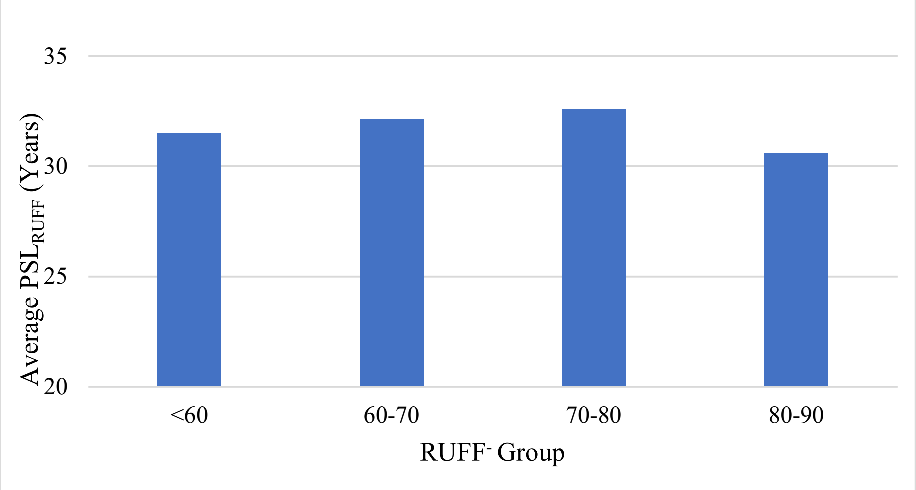


Fig. 5. Average PSL$_{RUFF}$ for the CSFDR projects at different RUFF$^-$ groups

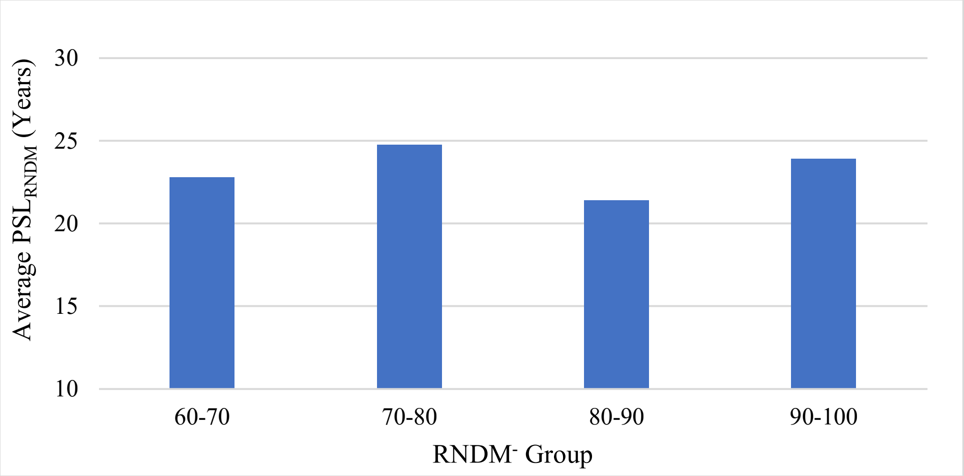


Fig. 6. Average PSL_{RNDM} for the CSFDR projects at different $RNDM^-$ groups

Expected Actual PSL of CSFDR Treatments in Louisiana

In the previous sections, the calculated PSL values were based on a specific distress without considering the other distresses that may cause earlier pavement failure. For a specific project, the expected actual PSL (PSL*) could be regarded as the minimum of PSL_{ALCR}, PSL_{RUT}, PSL_{RNDM}, and PSL_{RUFF}, and the corresponding distress could be reported as the limiting (i.e., controlling) distress. Therefore, Dataset 1 in Table 1 was used in this section to determine PSL* and the limiting distress for all the 122 CSFDR projects, see Figure 7. The CSFDR projects had an average PSL* of 18.6 ± 1.2 years at 95% confidence level. Figure 8 presents the limiting distresses for the 122 CSFDR projects. As shown in Figure 8, random cracking was the limiting distress for the majority of the projects (about 40% of the projects), which agrees with the results of the previous analysis. This could be attributed to the development of shrinkage cracks due to cement stabilization.

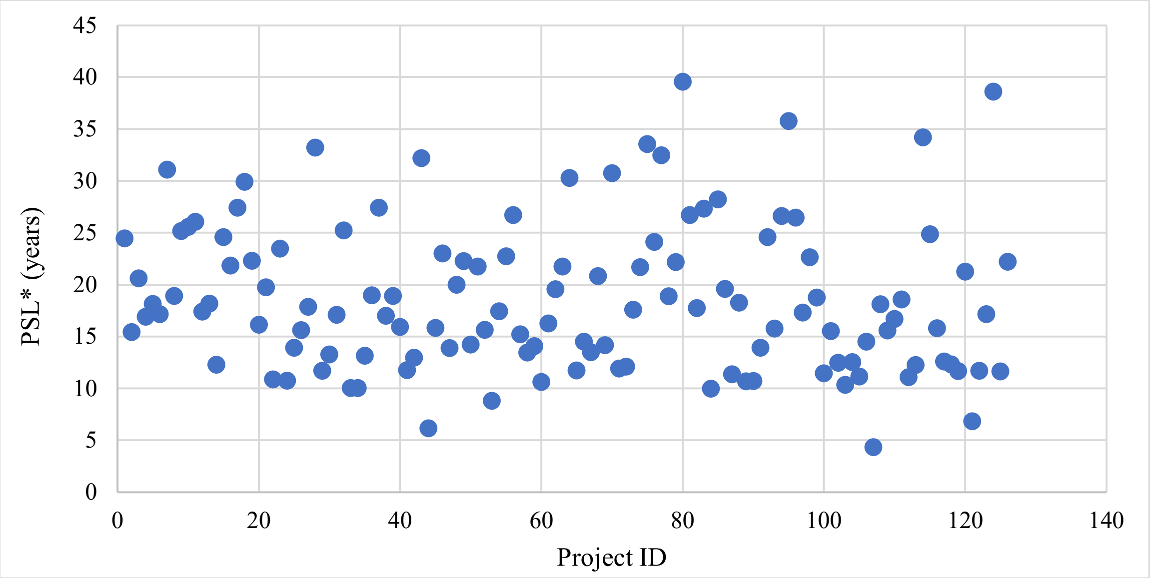


Fig. 7. Expected actual Pavement Service Life (PSL*) for the Analyzed Projects

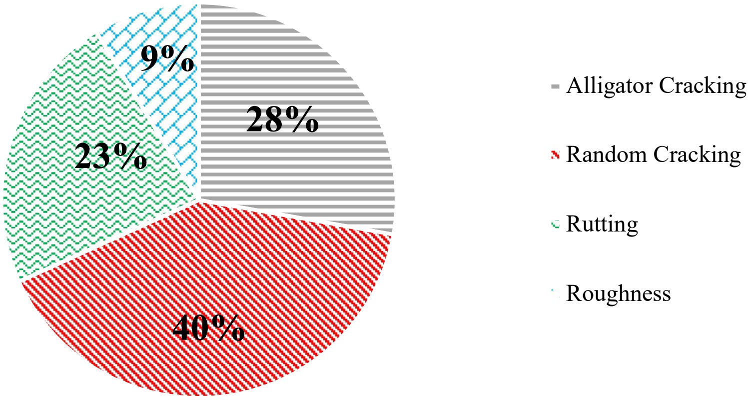


Fig. 8. Limiting distress in the CSFDR projects

Impact of Traffic on PSL* of CSFDR

To evaluate the impact of traffic on the long-term field performance of CSFDR, all the 122 CSFDR projects (Dataset 1 in Table 1) were grouped based on the Average Daily Traffic (ADT) at the treatment application date. The ADT groups were: “0-5,000” vehicles per day (VPD), “5,000-10,000” vpd, and “over 10,000” vpd. For each group, the average PSL* was computed, and statistical t-tests were conducted between the different groups, see Table 3. As expected, the PSL* increased with lower ADT (“0-5,000” group had the highest PSL* while “over 10,000” group had the lowest PSL*). The P-value between these two groups indicate that the impact of traffic is significant and should be considered when analyzing the long-term field performance of CSFDR treatments.

Table 3. Results of t-tests (traffic analysis)

ADT Group	**0-5,000**	**5,000-10,000**	**0-5,000**	**Over 10,000**
Mean PSL* (years)	18.9	17.8	18.9	13.7
Count (n)	109	9	109	4
P-value	0.5		0.01	

Expected Actual PSL of CSFDR Treatments in Terms of Traffic (PSLt*)

Generally, a limitation of the PSL definition is that it predicts the service life of the pavement without taking the traffic volume into account. Therefore, in this section, Dataset 1 in Table 1 was used to calculate the expected actual PSL in terms of cumulative truck traffic (instead of number of years) for all the 122 CSFDR projects. Figure 9 presents the calculation of the expected actual

PSL in terms of truck number (PSL_t*) for one of the CSFDR projects as an example. The results indicated that the 122 CSFDR projects had an average PSL_t* of 2.81 ± 0.5 million trucks at 95% confidence level.

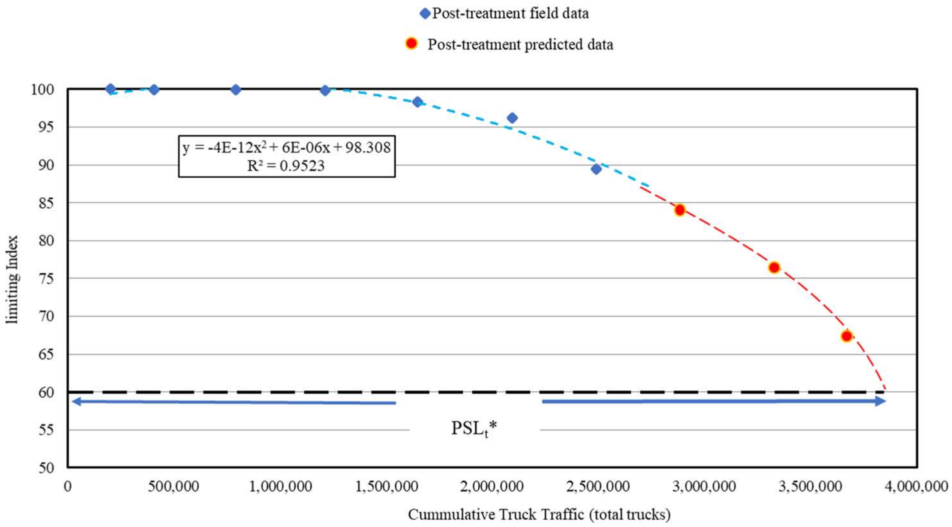


Fig. 9. Calculation of PSLt*

Effect of AC Overlay Thickness on PSL* and PSLt* of CSFDR

To quantify the impact of the applied asphalt overlay thickness on the long-term field performance of CSFDR (PSL* and PSL_t*), the average PSL* and PSL_t* for the CSFDR projects in Dataset 1 were computed and plotted against the applied overlay thickness, see Figure 10. To eliminate the effect of traffic, only projects within the "0-5,000" ADT group were considered in this analysis. This ADT group was selected because in Louisiana most of the CSFDR projects are applied to roads with ADT in this range as shown in Table 3 (out of the total 122 projects included in the analysis, 109 projects (almost 90%) were in the "0-5000" ADT group). As expected, thicker asphalt overlay thickness yielded longer service life for CSFDR (either PSL* or PSL_t*).

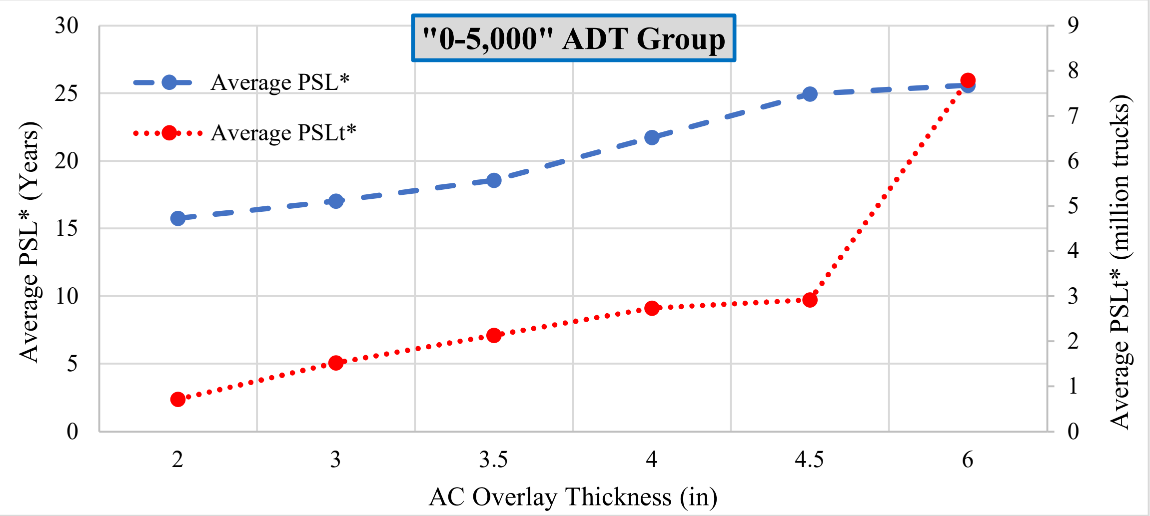


Fig. 10. Average PSL* and PSLt* for different overlay thickness of CSFDR treatments

5.1.3 Model Development

As shown in Figure 10, PSL_t* is significantly dependent on the applied asphalt overlay thickness. Therefore, a non-linear regression model was developed to predict the PSL_t* of CSFDR based on the applied asphalt overlay thickness (t) and the ADT at the time of treatment application. About 80% of Dataset 1 (98 projects) were used to fit the model and 20% of the data (24 projects) were used to validate and test the model. The fitted model developed after performing non-linear regression analyses on the PSL_t* as a dependent variable and ADT and t as independent variables, was as follows:

$$PSL_t^* = (-540706 \times t) + (177980 \times t^2) + (705.5 \times ADT) + (7.34 \times 10^{-5} \times ADT) + 582438 \qquad (8)$$

Figure 11 and Figure 12 present the actual and predicted PSL_t* using the fitting and testing data, respectively. Based on both figures, it is clear that the proposed model predicted PSL_t* with an acceptable level of accuracy as supported by the coefficient of determination (R^2) and the Root Mean Square Error (RMSE) shown in the figures. For the training data, the R^2 and RMSE were approximately 0.90 and 0.7 million trucks, respectively, while for the testing data, the R^2 and RMSE were about 0.84 and 1.1 million trucks, respectively. Therefore, the model described in Equation (8) could be utilized by transportation agencies in hot and humid climates to predict the service life of CSFDR treatments based on the project conditions and plan for future maintenance and rehabilitation actions.

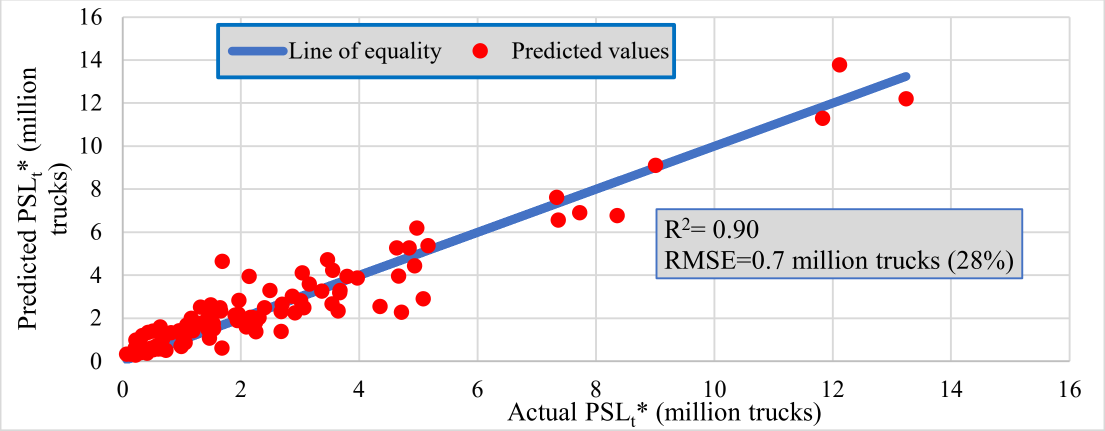


Fig. 11. Predicted PSLt* versus actual PSLt* using fitting data

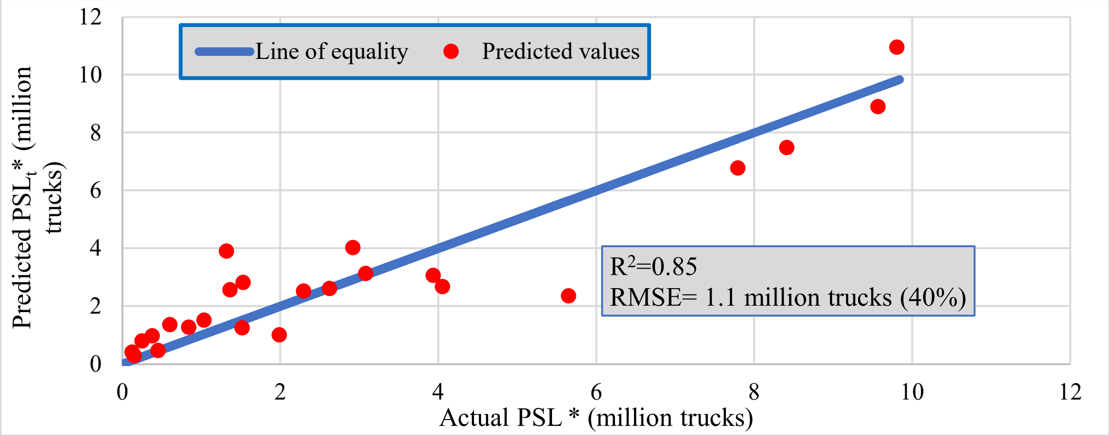


Fig. 12. Predicted PSLt* versus actual PSLt* using training data

5.1.4 Cost-Effectiveness

The cost effectiveness of the CSFDR projects was assessed using the Equivalent Annual Cost (EAC) approach. The EAC approach was successfully used in previous studies *(29)* because it is relatively simple, straightforward, and comprehensive. The EAC is calculated as follows *(29):*

$$\mathrm{EAC_i} = \frac{\mathrm{C}}{\mathrm{PSL_i}} \tag{9}$$

where EAC= equivalent annual cost; c= project unit cost ($/lane-mile); and i= subscript representing the distress type.

In this section, $\mathrm{EAC_{ALCR}}$, $\mathrm{EAC_{RUT}}$, $\mathrm{EAC_{RUFF}}$, and $\mathrm{EAC_{RNDM}}$ were calculated for Datasets 2, 3, 4, and 5, respectively. For comparison purposes, the $\mathrm{EAC_{ALCR}}$, $\mathrm{EAC_{RUT}}$, $\mathrm{EAC_{RUFF}}$, and $\mathrm{EAC_{RNDM}}$ for a total of 144 conventional mill and overlay projects in Louisiana (25.4 mm [1 in.] milling followed by 50.8 mm [2 in.] to 101.6 mm [4 in.] asphalt overlay) were obtained from a previous study *(27)*. Figure 13 presents the average $\mathrm{EAC_i}$ for the CSFDR and mill/overlay projects. As shown, for all the distresses, the CSFDR had higher EAC than the mill and overlay projects suggesting that CSFDR is not always cost-effective. Therefore, CSFDR shall only be selected for projects when base failures exist, which may be identified through core extractions or FWD measurements.

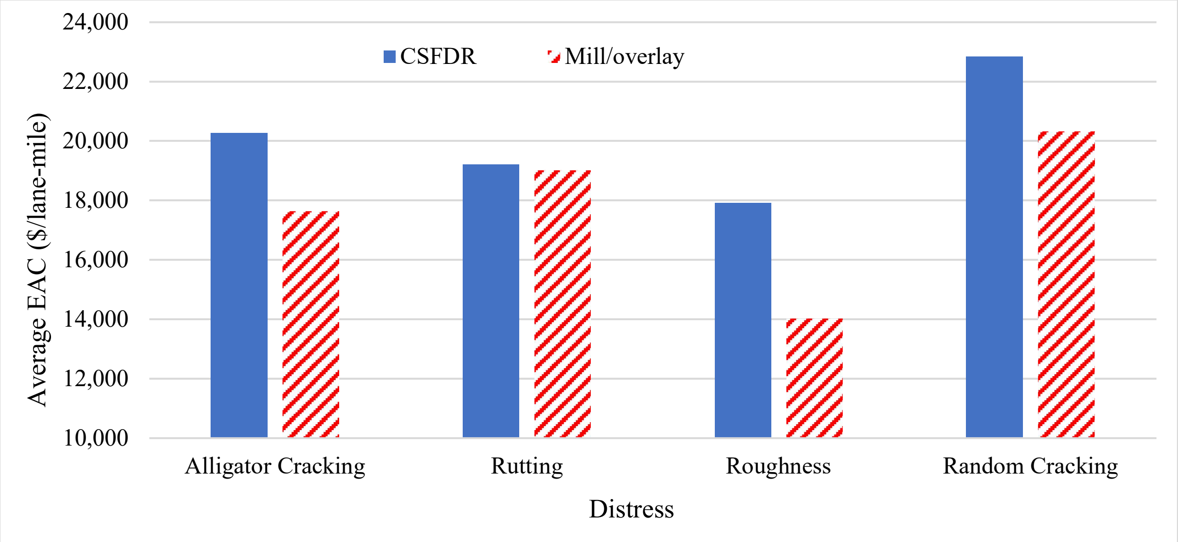
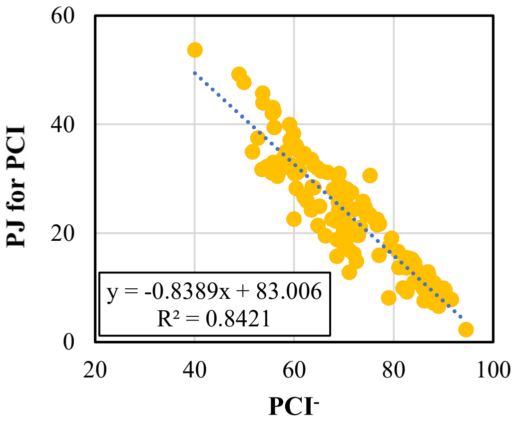


Fig. 13. Average EAC of CSFDR and mill/overlay projects for different indices

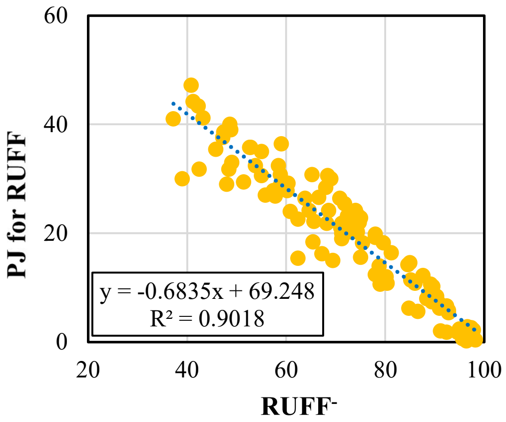
5.2. Ultra-Thin Overlay

5.2.1 Immediate Benefits

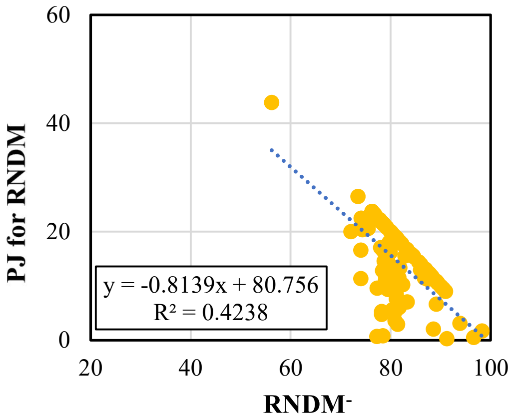
The immediate benefit of UTO was evaluated in terms of Performance Jump (PJ), which was calculated for all the data points (log-miles) in Table 2. Datasets 6, 7, 8, 9 and 10, presented in Table 2, were utilized to calculate the PJ for every data point (log-mile) by subtracting the pre-treatment index from the first collected index after UTO application. Figure 14 shows the PJ for all the log-miles for the different indices. As expected, almost all the analyzed log-miles had positive PJ for all the indices with average values of 23.6 ± 10.5, 19.6 ± 12.1, 14.6 ± 6.9, 21.9± 11.3, and 18.0 ± 18.4 for PCI, RUFF, RNDM, ALCR, and RUT, respectively. Therefore, the long-term field performance evaluation conducted in the following sections was performed in terms of the overall pavement condition (PCI), which considers all the surface distresses in the pavement as shown in Equation (1).



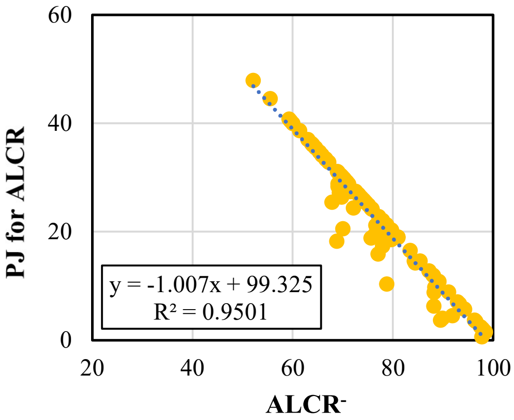
(a)



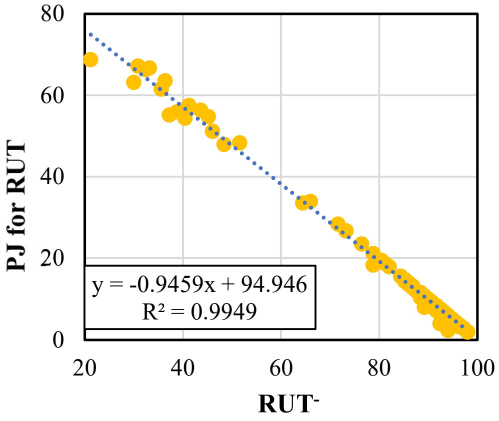
(b)



(c)



(d)



(e)

Figure 14. Correlation between the Performance Jump and Pre-treatment Pavement Conditions for (a) PCI, (b) RUFF, (c) RNDM, (d) ALCR, and (e) RUT

5.2.2 Long-Term Benefits

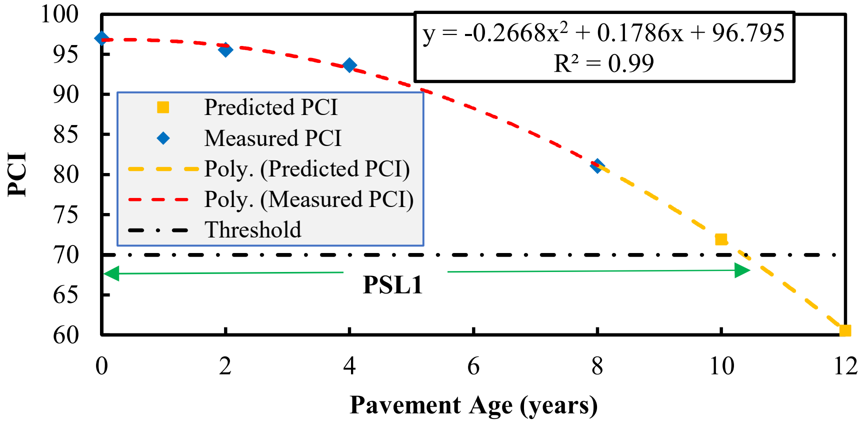
Impact of UTO on Overall Pavement Conditions

The long-term field performance of UTO was assessed in terms of the extension in pavement service life (ΔPSL), which was calculated for all the 126 log-miles in Dataset 6 (see Table 2). To determine ΔPSL for each log-mile, two performance curves were plotted before and after UTO application with the collected PCI plotted against age, see Figure 15. PCI data exactly at the treatment application date, which corresponds to year zero, were extrapolated using the collected PCI after treatment application. Quadratic polynomial models were then used to fit the data as shown in Figure 15. Using the fitted models, the PSL before UTO application (PSL 1) and after UTO application (PSL 2) were calculated as the number of years for the PCI to drop to a threshold PCI, see Figure 15. A threshold index of 70 was considered for UTO. This threshold PCI was selected to match the LaDOTD trigger values for microsurfacing on arterials or collectors since most of the analyzed roads in this study were either arterial or collector roads. Finally, ΔPSL was calculated as follows:

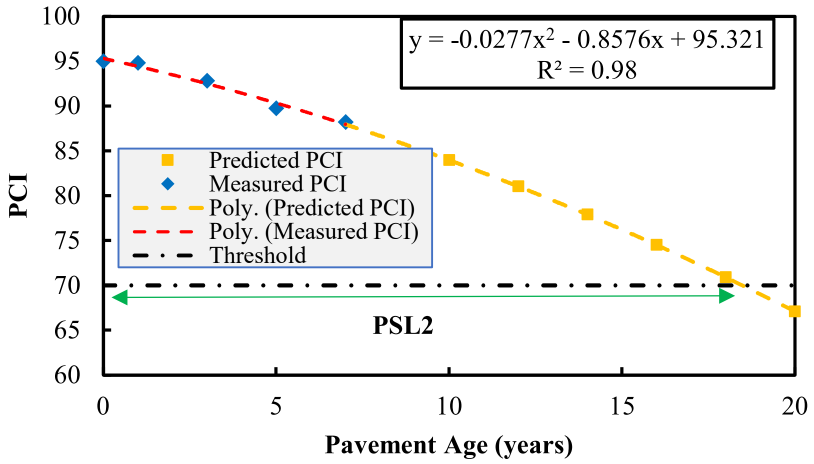
$$\Delta PSL = A + PSL\ 2 - PSL\ 1 \qquad (10)$$

where,

A is the pavement age when the UTO was applied; PSL 1 and PSL 2 are the PSL of the pavement before and after UTO application, respectively.



(a)



(b)

Figure 15. Performance Curves for one of the analyzed log-miles (a) before and (b) after UTO application

Figure 16 presents the computed ΔPSL for all the 126 log-miles against the corresponding PCI^{-}. Based on Figure 16, the following can be concluded:

- For all the 126 log-miles, ΔPSL ranged between 0.7 and 21.5 years, with an average value of 8.7 years and lower and upper limits of 95% confidence interval (C.I) of 8.1 and 9.4 years, respectively. The upper and lower 95% C.I limits are comparable to the results reported by Cooper and Mohammad *(23)* in Louisiana that indicated that UTO extended the PSL of asphalt pavements by about 10 years.
- The UTO benefits in terms of ΔPSL is dependent on the pre-treatment condition (PCI^{-}). The general trend in Figure 16 suggests that higher PCI^{-} values yielded lower ΔPSL. This may be attributed to the fact that when UTO is applied too soon, it is less effective since almost all the remaining performance of the original pavement is still unused.

To evaluate the impact of traffic on the long-term field performance of UTO, the ΔPSL computed for all the 126 data points (presented in Figure 16) were grouped based on the Average Daily Truck Traffic (ADTT) at the UTO application date. The ADTT groups were "0-500" trucks per day, "500-1,000" trucks per day, and "over 1,000" trucks per day. For each group, the average ΔPSL was computed, and statistical t-tests were conducted between the different groups, see Table 4. As expected, ΔPSL increased with lower ADTT (the "0-500" group had the highest ΔPSL while the "over 1,000" group had the lowest ΔPSL). The low P-value between the "0-500" and "over 1,000" groups indicate that the impact of traffic is significant and should be considered when analyzing the long-term field performance of UTO treatments.

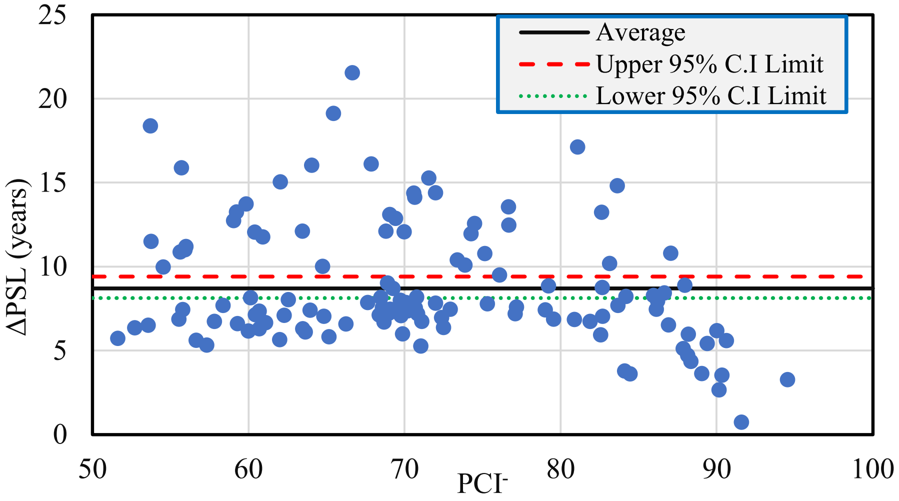


Figure 16. ΔPSL for all the 126 log-miles versus PCI-

Table 4. Results of t-tests (traffic analysis)

ADTT Group (trucks per day)	**0-500**	**500-1,000**	**0-500**	**Over 1,000**
Mean ΔPSL (years)	9.1	8.1	9.1	5.6
Count (n)	102	16	102	8
P-value	0.14		0.000008	

Impact of UTO on Surface Distresses

In this section, the long-term field performance of UTO was evaluated based on the RNDM, RUT, RUFF, and ALCR (instead of PCI). This was done by re-calculating ΔPSL using the same aforementioned procedure (Equation 10) using Datasets 7 to 10 (described in Table 2). Table 5 presents descriptive statistics for the re-calculated ΔPSL for each dataset. As shown in Table 5, the UTO was effective in correcting all the pavement surface distresses on the long-term. In specific, the UTO extended the PSL by 9.1±1.7 years; 7.0±1.71 years; 9.7±1.5 years; and 9.5±0.7 years for RUFF, RNDM, ALCR, and RUT, respectively. Given that the average ΔPSL for RNDM was the lowest when compared to other surface distresses, it is reasonable to conclude that random cracking is the common mode of failure in UTO.

Table 5. Descriptive statistics for ΔPSL re-calculated based on RUFF, RNDM, ALCR, and RUT

Dataset ID	Distress Index	Count	Average ΔPSL (years)	95% Lower C.I Limit for ΔPSL (years)	95% Upper C.I Limit for ΔPSL (years)
2	RUFF	112	9.1	7.4	10.8
3	RNDM	111	7.0	5.9	8.2
4	ALCR	96	9.7	7.9	11.2
5	RUT	106	9.5	8.8	10.2

5.2.3 Model Development

As shown in the previous section, the benefits of UTO (ΔPSL in terms of PCI) is significantly dependent on the pre-treatment pavement condition (PCI^-) and ADTT. Therefore, a non-linear regression model was developed to predict ΔPSL (in terms of PCI) of UTO treatments based on the corresponding PCI^-, ADTT at the time of treatment application, and road functional class (FC). About 80% of Dataset 6 (100 log-miles) were used to fit the model and the remaining 20% (26 log-miles) were used to validate and test the model. The fitted model developed after performing non-linear regression analyses on the ΔPSL as a dependent variable and PCI^-, ADTT and FC as independent variables, was as follows:

$$\Delta\mathrm{PSL} = (-0.009895\ \mathrm{PCI}^{-2}) + (1.304178\ \mathrm{PCI}^{-}) + (-0.00000175\ \mathrm{ADTT}^2) + (0.002124\ \mathrm{ADTT}) + (-1.894603\mathrm{FC}^2) + (9.293313\ \mathrm{FC}) - 42.461634 \qquad (11)$$

where,

FS= road functional class. A numerical value of 1 is used for local roads; 2 for major collectors; 3 for minor arterials; and 4 for minor collectors.

Figure 17 and Figure 18 present the actual and predicted ΔPSL using the fitting and testing data, respectively. It is worth noting that the testing data were not used in the model training, and thus would reflect the model accuracy. Based on Figures 17 and 18, it is clear that the proposed model predicted ΔPSL with a reasonable level of accuracy as supported by the coefficient of determination (R^2) and the Root Mean Square Error (RMSE) shown in the figures. For the fitting data, the R^2 and RMSE were approximately 0.85 and 0.09 years, respectively, while for the testing data, the R^2 and RMSE were about 0.79 and 0.87 years, respectively. Therefore, the model described in Equation (11) could be used by transportation agencies in hot and humid climates to predict the ΔPSL of UTO treatments based on the project conditions. This will help them make effective decisions for the maintenance and rehabilitation of their pavements.

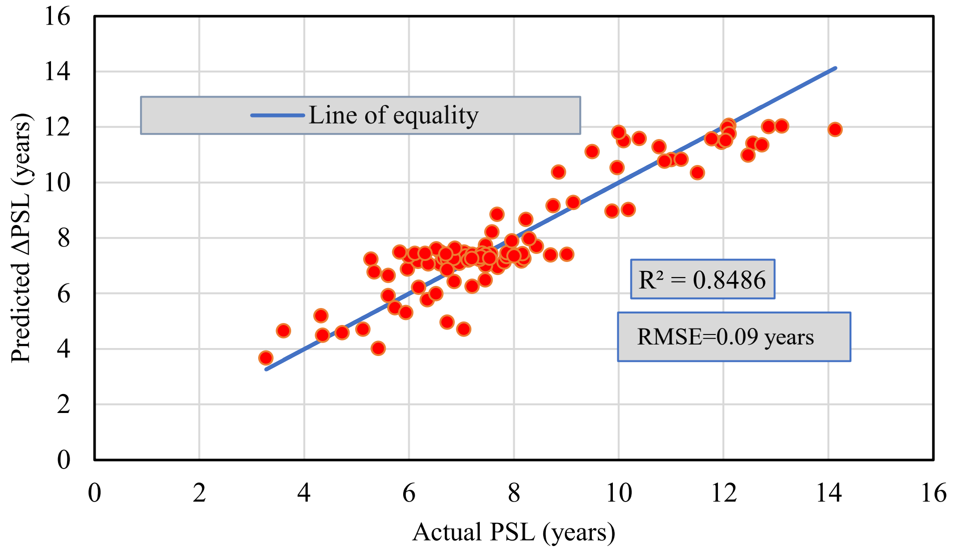


Figure 17. Predicted ΔPSL versus actual ΔPSL for fitting data

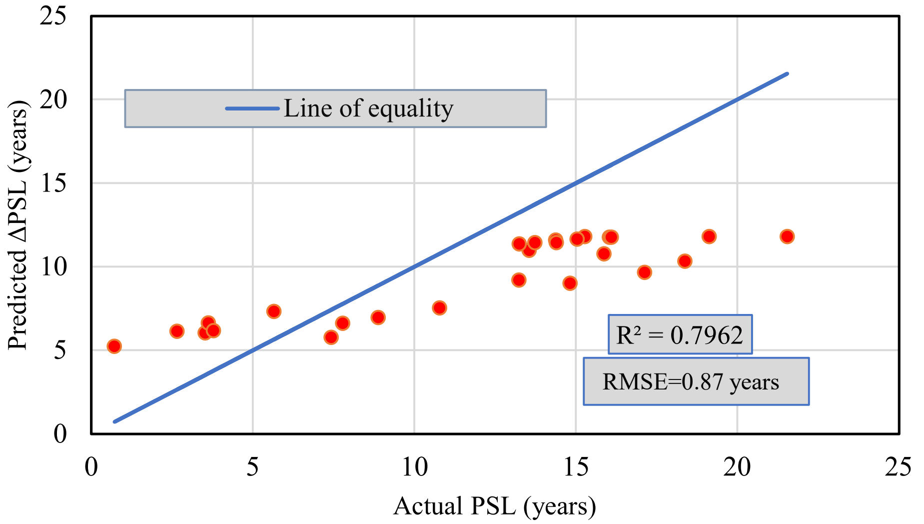


Figure 18. Predicted ΔPSL versus actual ΔPSL for testing data

5.2.4 Cost-Effectiveness

Life-cycle cost analysis in the form of equivalent uniform annual costs (EUAC) was conducted in this study to assess the cost-effectiveness of UTO treatments. The performance of the UTO-treated pavement was compared with the performance of original pavement without any maintenance, and the Benefit-Cost (B/C) ratio was calculated as follows *(30):*

$$\frac{\mathrm{B}}{\mathrm{C}} = \frac{\mathrm{EUAC}_{\mathrm{do\ nothing}} - \mathrm{EUA\ \ treatment}}{\mathrm{EUAC}_{\mathrm{UTO}}} \qquad (12)$$

$$\mathrm{EUAC}_{\mathrm{do\ nothing}} = \mathrm{NPV1} \times \left[\frac{(1+\mathrm{i})^{\mathrm{PSL1}}}{(1+\mathrm{i})^{\mathrm{PSL1}} - 1}\right] \qquad (13)$$

$$\mathrm{EUAC}_{\mathrm{UTO}} = \mathrm{NPV2} \times \left[\frac{(1+i)^{\mathrm{PSL1}+\Delta\mathrm{PSL}}}{(1+i)^{\mathrm{PSL1}+\Delta\mathrm{PSL}}{}_{-1}}\right] \quad (14)$$

$$\mathrm{EUAC}_{\mathrm{treatment}} = (\mathrm{NPV1} + \mathrm{NPV2}) \times \left[\frac{(1+i)^{\mathrm{PSL1}+\Delta\mathrm{PSL}}}{(1+i)^{\mathrm{PSL1}\ \ \Delta\mathrm{PSL}}{}_{-1}}\right] \quad (15)$$

where,

NPV 1 = the net present value (NPV) of the initial cost of baseline pavement in \$/mile; NPV 2 = NPV of the cost of UTO in \$/mile;
i= interest rate; and
PSL1 and ΔPSL are as previously defined.

A B/C ratio greater than one would indicate that the UTO benefits exceeded its costs; hence, it is cost-effective. The B/C ratio was calculated for all the 126 log-miles (Dataset 6) using the corresponding PSL1, ΔPSL, NPV 2 (based on the UTO unit cost), and NPV 1 (based on the unit cost of the original pavement before UTO application). For all the log-miles, i was assumed 6%. Figure 19 presents the resulting B/C ratio for all the 126 log-miles. As shown, 87 out of the total 126 log-miles (69%) had B/C ratio greater than one (cost-effective) indicating that UTO was cost-effective when used in hot and wet climates.

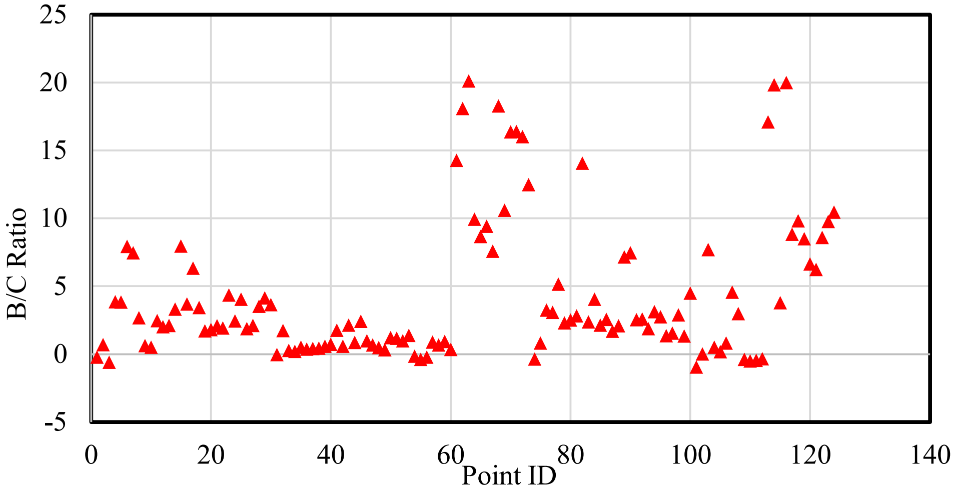


Figure 19. B/C ratio for all the 126 log-miles

6. CONCLUSION

The ultimate objective of this research project was to develop decision trees or models that could help state agencies select pavement maintenance and rehabilitation activities in South-Central United States. This was achieved through evaluating the field performance and cost-effectiveness of CSFDR and UTO projects in Louisiana. Based on the results of this study, the following conclusions were drawn:

- CSFDR had a significant immediate effect on ALCR, RUT, RNDM, and RUFF indicating that it properly corrected all existing pavement deficiencies. For all the distresses, there was a strong correlation between the performance jump and the pre-treatment pavement conditions.
- The long-term field performance of CSFDR primarily depends on the pre-treatment pavement conditions, applied overlay thickness, and traffic level. The 122 CSFDR projects had an average service life of 18.6 ± 1.2 years at 95% confidence level. In terms of traffic, the CSFDR projects had an average life of 2.81 ± 0.5 million trucks at 95% confidence level.
- Random cracking was the primary cause of long-term failure in the evaluated CSFDR projects. This could be attributed to the development of shrinkage cracks, which is a common problem with cement stabilization in Louisiana. These cracks can reflect through the asphalt surface in a short period of time and accelerate pavement deterioration.
- CSFDR projects are less cost-effective than conventional mill and overlay projects in Louisiana. Therefore, CSFDR shall only be selected for field projects in which base failure exists.
- The application of UTO had a significant immediate impact on all the surface distresses. Most of the analyzed log-miles had a positive PJ with an average value of 23.6 ± 10.5, 19.6 ± 12.1, 14.6 ± 6.9, 21.9± 11.3, and 18.0 ± 18.4 for PCI, RUFF, RNDM, ALCR, and RUT, respectively.
- In terms of PCI, ΔPSL for all the 126 UTO log-miles ranged between 0.7 and 21.5 years, with an average value of 8.7 years and lower and upper limits of 95% confidence interval (C.I) of 8.1 and 9.4 years, respectively. This variation in ΔPSL could be attributed to the variation in pre-treatment pavement condition (PCI^-) and traffic level that seemed to significantly affect the long-term field performance of UTO.
- The UTO extended the PSL by 9.1±1.7 years; 7.0±1.71 years; 9.7±1.5 years; and 9.5±0.7 years for RUFF, RCI, ALCR, and RUT, respectively.
- Random cracking was the common mode of failure for UTO treatments in Louisiana.
- Out of the total 126 log-miles, 87 log-miles (69%) had B/C ratio greater than one (cost-effective) indicating that UTO was cost-effective in most of the cases when used in hot and wet climates.

Based on the results of the analysis, two non-linear regression models were developed with an acceptable level of accuracy to predict the pavement service life of CSFDR and UTO treatments based on the project conditions. These models could be utilized by transportation agencies in hot and humid climates to predict the service life of CSFDR and UTO treatments and plan for future maintenance and rehabilitation actions.

REFERENCES

1. AASHTO Highway Subcommittee on Maintenance, as cited in FHWA's "Memorandum on Pavement Preservation Definitions."
2. Preservation, Pavement. "A Road Map for the Future- ideas, strategies, and techniques for pavement preservation", US Department of Transportation, Federal Highway Administration, 1998.
3. LaDOTD, "Guidelines on the Application of Preventive Maintenance and Rehabilitation Practices for Pavement Preservation", Pavement Preservation Manual, Volume 1, 2010.
4. Texas Department of Transportation (2005), "Guidelines for Modification and Stabilization of Soils and Base for Use in Pavement Structures", Construction Division, Materials & Pavements Section, Geotechnical, Soils & Aggregates Branch.
5. Wu, Zhong, Yilong Liu, and Ferdous Intaj. Minimizing Shrinkage Cracking in Cement-Stabilized Bases through Micro-Cracking. No. FHWA/LA. 18/588. Louisiana Transportation Research Center, 2018.
6. Gaspard, Kevin. Evaluation of cement treated base courses: technical assistance report. No. 00-1TA. Louisiana Transportation Research Center, 2000.
7. Luhr, David Robert, Wayne S. Adaska, and Gregory E. Halsted. "Guide to Full-Depth Reclamation (FDR) with Cement." (2007).
8. Grogan, W. P., Weiss Jr, C. A., & Rollings, R. S. (1999). Stabilized base courses for advanced pavement design report 1: literature review and field performance data. U.S Department of Transportation, Report No. DOT/FAA/AR-97/65.
9. Little, D. N., Scullion, T., Kota, P. B. V. S., & Bhuiyan, J. (1995). Guidelines for mixture design and thickness design for stabilized bases and subgrades (No. FHWA/TX-95/1287-3F).
10. Mohammad, Louay, and Shadi Saadeh. "Performance evaluation of stabilized base and subbase material." GeoCongress 2008: Geosustainability and Geohazard Mitigation. 2008. 1073-1080.
11. Hajj, R., A. Filonzi, A. Smit, and A. Bhasin. Design and Performance of Mixes for Use as Ultrathin Overlay. Journal of Transportation Engineering, Part B: Pavements, Vol. 145, No. 3, 2019, p. 04019026.
12. Kandhal, P. S., and L. Lockett. Construction and Performance of Ultrathin Asphalt Friction Course. 1997.
13. Sauber, R. W. Thin Overlays Pavement Preservation NJDOT. 2009.
14. Pretorius, F. J., J. C. Wise, and M. Henderson. Development of application differentiated ultra-thin asphalt friction courses for southern African application. Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04) ISBN, No. September, 2004, pp. 1–15.
15. Estakhri, C. K., and J. W. Button. Evaluation and Monitoring of NOVACHIP TM Asphalt Pavement Process Unclassified. 1993.

16. Hanson, D. I. Construction and Performance of an Ultrathin Bonded Hot-Mix Asphalt Wearing Course. Transportation Research Record: Journal of the Transportation Research Board, Vol. 1749, No. 1, 2001, pp. 53–59.
17. Taha, R., Al-Harthy, A., Al-Shamsi, K., & Al-Zubeidi, M. (2002). Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases. Journal of materials in civil engineering, 14(3), 239-245.
18. Francois, Andrae Anthony. "Evaluating the impact of different types of stabilized bases on the overall performance of flexible pavements." (2017).
19. Jones, D., Wu, R., & Louw, S. (2019). Comparison of Full-Depth Reclamation with Portland Cement and Full-Depth Reclamation with No Stabilizer in Accelerated Loading Test. Transportation Research Record, 2524(1), 133-142.
20. Amarh, E. A., Flintsch, G. W., Fernández-Gómez, W., Diefenderfer, B. K., & Bowers, B. F. (2019). Eight-Year Field Performance of Portland Cement and Asphalt Stabilized Full-Depth Reclamation Projects. In Airfield and Highway Pavements 2019: Design, Construction, Condition Evaluation, and Management of Pavements (pp. 263-272). Reston, VA: American Society of Civil Engineers.
21. Musa Ruranika, M., and J. Geib. Performance of Ultra-Thin Bounded Wearing Course (UTBWC) Surface Treatment On US-169 Princeton, MN. 2007.
22. Russell, M. A., L. M. Pierce, J. S. Uhlmeyer, and K. W. Anderson. NovaChip. 2008.
23. Cooper, S. B., and L. N. Mohammad. Nocachip Surface Treatment Six Year Evaluation. Louisiana Transportation Research Center, 2004.
24. Musty, H., and M. Hossain. Performance of ultra-thin bituminous overlays. American Society of Civil Engineers (ASCE), 2014.
25. Chen, D. H., and T. Scullion. Very Thin Overlays in Texas. Construction and Building Materials, Vol. 95, 2015, pp. 108–116.
26. Mousa, M. R., M. A. Elseifi, M. Z. Bashar, Z. Zhang, and K. Gaspard. Optimizing the Cost-Effectiveness and Time of Application of Microsurfacing. Journal of Transportation Engineering, Part B: Pavements, Vol. 147, No. 1, 2021.
27. Mousa, M., M. A. Elseifi, and A. Abdel-Khalek. Development of Tree-Based Algorithm for Prediction of Field Performance of Asphalt Concrete Overlays. Journal of Transportation Engineering, Part B: Pavements, 2019.
28. Mousa, M. R., Elseifi, M. A., Bashar, M. Z., Zhang, Z., Gaspard, K., & Free, K. (2019). Cost Effectiveness and Optimal Timing of Crack Sealing in Asphalt Concrete Overlays. Journal of Transportation Engineering, Part B: Pavements, 145(3), 04019029.
29. Smith, K. L., and A. R. Romine. 2001. Materials and procedures for sealing and filling cracks in asphalt-surfaced pavements. Rep. No. FHWA-RD-99-147. Washington, DC: Federal Highway Administration.
30. Morian, D. A. *Cost Benefit Analysis of Including Microsurfacing in Pavement Treatment Strategies & Cycle Maintenance.* 2011.