Application and Validation of Remaining Service Interval Framework for Pavements

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FOREWORD

The pavement remaining service interval (RSI) terminology was formulated to remove the confusion caused by the multitude of meanings assigned to the various forms of pavement remaining service life (RSL) terminology. The RSI concept considers the complete maintenance and rehabilitation activity of the pavement system and does not simply consider the end of life as promulgated by the RSL philosophy. This report answers the following questions: should the time until a condition exceeds a threshold, or the optimum time to apply a rehabilitation treatment is reached, be used as the basis for rehabilitation RSI? When the condition of a pavement drops to a level that is lower than the reconstruction threshold, should a negative RSI be reported? This report provides more evidence of merit to move the pavement community away from a worst first approach and toward a more optimal mixture of pavement preservation and rehabilitation treatments based on proper consideration of lifecycle cost concepts. The project- and network-level analyses presented in this report represent an important milestone in the evolution of pavement and asset management systems. This report is intended for use by pavement management engineers and pavement investment decisionmakers across the United States.

Mayela Sosa
Acting Director, Office of Infrastructure
Research and Development

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16. Abstract

The pavement remaining service interval (RSI) terminology was developed to remove confusion caused by the multitude of meanings assigned to the various forms of pavement remaining service life (RSL). The RSI concept considers the complete maintenance and rehabilitation (M&R) activity of the pavement system and does not simply consider the end of life as promulgated by the RSL philosophy. The goal of this project was to demonstrate and further develop the application of the pavement RSI concept using real data from two State pavement management systems and the Highway Performance Monitoring System 2010+ dataset. Project-level analysis addressed gaps in the network- and strategic-level analyses. The results from the validation efforts support the conclusion that the RSI represents a valid approach to determining and communicating future M&R needs of a pavement instead of defining pavement life using a single number as in RSL. Those results also show that RSL is essentially not related to the time until the next pavement treatment in an optimal strategy.

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	average annual daily traffic
AASHTO	American Association of State Highway Transportation Officials
AC	asphalt concrete
ANOVA	analysis of variance
BCR	benefit-cost ratio
CCI	Critical Condition Index
CDOT	Colorado Department of Transportation
CPM	capital preventative maintenance
DL	drivability life
EUAC	equivalent uniform annual cost
FCI	Functional Cracking Index
FHWA	Federal Highway Administration
FWD	falling weight deflectometer
HERS	Highway Economics Requirements System
HMA	hot-mix asphalt
HPMA	Highway Pavement Management Application
HPMS	Highway Performance Monitoring System
IRI	International Roughness Index
JULEA	*Jacob Uzan Layered Elastic Analysis*
LCC	lifecycle cost
LCCA	lifecycle cost analysis
LDR	load-related distress rating
LLCC	lowest lifecycle cost
LOS	level of service
LTPP	Long-Term Pavement Performance
M&R	maintenance and rehabilitation
MDOT	Michigan Department of Transportation
MDSHA	Maryland State Highway Administration
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
MnDOT	Minnesota Department of Transportation
NAPCOM	national pavement cost model
NCDOT	North Carolina Department of Transportation
NDR	non-load-related distress rating
NHS	National Highway System
NPV	net present value
PCC	portland cement concrete
PHT	Pavement Health Track
PMS	pavement management system
PPC	pavement profile condition
PRC	pavement rutting condition
PSC	pavement structural condition
R&R	rehabilitation and reconstruction
RQFS	Road Quality Forecasting System
RQI	Ride Quality Index

RSI	remaining service interval
RSL	remaining service life
SCI	Structural Cracking Index
TSDD	traffic speed deflection device
VDOT	Virginia Department of Transportation
VMT	vehicle-miles traveled
WSDOT	Washington State Department of Transportation

CHAPTER 1. INTRODUCTION

BACKGROUND

The pavement remaining service interval (RSI) terminology was developed to eliminate the ambiguity associated with the multitude of meanings assigned to the various forms of pavement remaining life terminology. Since pavements are repairable systems, the use of the word "life" is improper because pavements do not "die;" correctable component failures do not define system life. While the basis of the concept was a shift in terminology, it required further development and refinement of computational algorithms and presentation techniques in order to find acceptance in practice.

The RSI concept was developed through the previous Federal Highway Administration (FHWA) project, "Definition and Determination of Remaining Service and Structural Life." The report that resulted from that project—*Reformulated Pavement Remaining Service Life Framework*—details the basic research technique of going back to first principles and defining the actual problem to be addressed.(1) The findings from this first-principles approach caused a radical shift away from further development of pavement remaining life approaches in favor of exploring replacement terminology that better described the different levels of pavement repair. The replacement terminology, RSI, was developed using the process illustrated in figure 1. The RSI concept considers the complete maintenance and rehabilitation (M&R) activity of the pavement system and does not simply consider the end of life as promulgated by the remaining service life (RSL) philosophy.

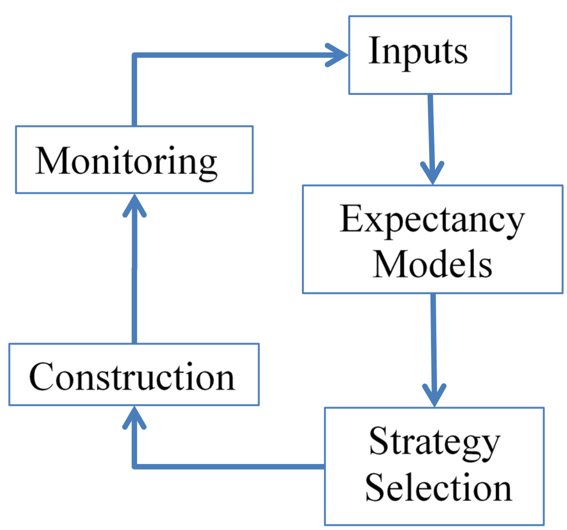
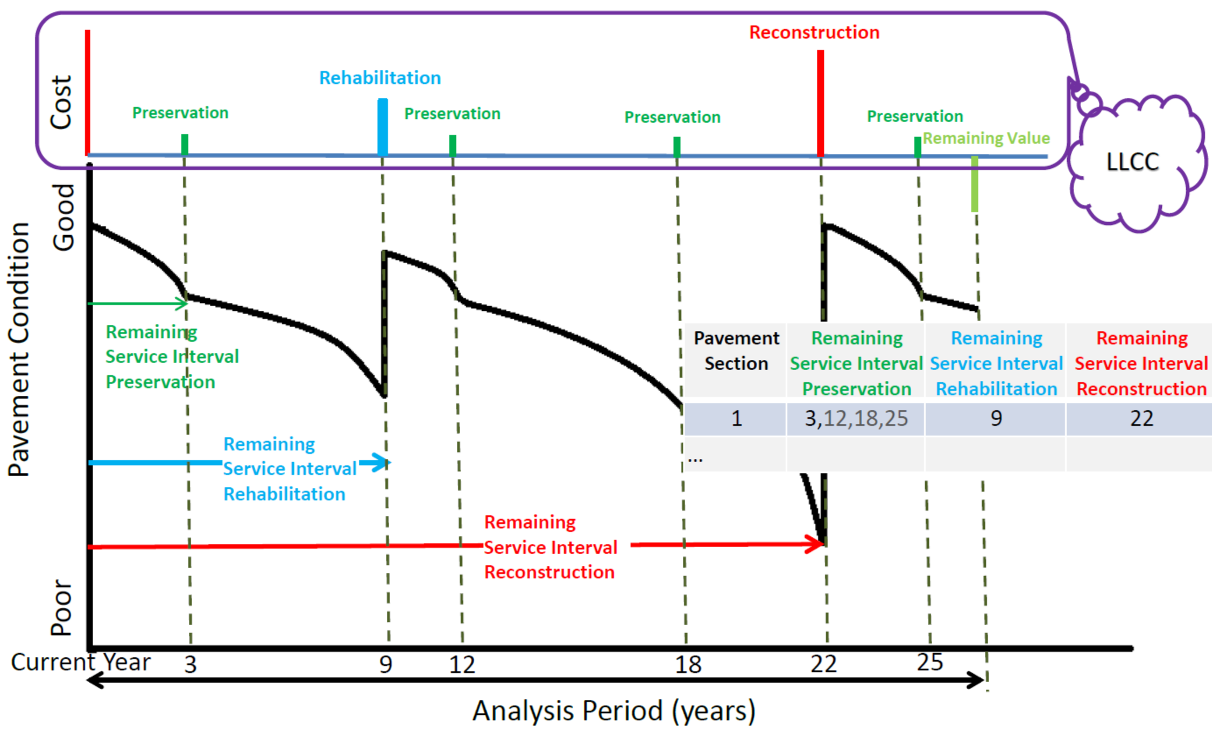


Figure 1. Illustration. Future pavement construction needs process.(1)

Figure 2 illustrates the RSI concept using limits for preservation, rehabilitation, and reconstruction. Starting with the current pavement condition, the preservation RSI is the time until the expectancy curve reaches the preservation limit. The rehabilitation RSI is the time until the expectancy curve reaches the rehabilitation limit with consideration to appropriate timed preservations treatments. Similarly, reconstruction RSI is the time until the expectancy curve reaches the reconstruction limit with consideration to appropriately timed preservation and rehabilitation treatments. In this figure, the pavement section has three RSI numerics based on pavement condition: $RSI_{Preservation}$, $RSI_{Rehabilitation}$, and $RSI_{Reconstruction}$. These limits represent condition thresholds below which the corresponding treatment will not be efficient for preservation and rehabilitation. This figure also illustrates some of the issues to be investigated in this study, including the following:

- Should the time until a condition exceeds a threshold or the optimum time to apply a rehabilitation treatment is reached be used as the basis for rehabilitation RSI?

- When the condition of a pavement drops to a level that is lower than the reconstruction threshold, should a negative RSI be reported?



LLCC = Lowest lifecycle cost.

Figure 2. Illustration. Pavement RSI concept.

With the passing of the *Moving Ahead for Progress in the 21st Century Act* in July 2012 emphasizing total asset management and the subsequent *Fixing America's Surface Transportation Act* passed in December 2015, the RSI concept is poised to help agencies use best practices with the goal of an ideal asset management and pavement management approach.[2,3] The RSI concept allows for agencies to optimize their investments based on the optimum timing to place a treatment instead of being threshold driven.

OBJECTIVES

The goal of this project was to demonstrate and further develop the application of the pavement RSI concept using data from two State pavement management systems (PMSs) and the Highway Performance Monitoring System (HPMS) 2010+ dataset. The specific objectives of the project were as follows:

- Conduct research to develop detailed analysis methodologies for the new pavement RSI concept developed in the recently completed FHWA research effort.
- Apply and validate the developed methodologies using a minimum of two State transportation department PMS datasets. The effort also used HPMS 2010+ datasets for similar validation for national-level analyses.

PROJECT APPROACH

The overall validation approach was to develop a general RSI algorithm and then implement the RSI using available data, models, and business rules. Within this approach, the benefits and limitations of the RSI were made clear, and the recommendations that were developed had direct implications for the current state of practice. However, when beginning the validation of the RSI, it became quickly evident that more fundamental questions related to pavement management practice needed to be resolved, including the influence of analysis periods on optimized maintenance strategies and the inclusion of structural measures to performance prediction. Therefore, the work presented in this report goes beyond simply validating the RSI concept; it includes research that is more fundamental to pavement management practices.

Although the initial project approach was to only consider State validation using two State transportation department PMSs (network level) and a national-level validation using HPMS 2010+ data and the Pavement Health Track (PHT) analysis tool (strategic level), through the course of the project, project-level analysis was also added to address gaps in the network and strategic level analyses.(4) The project level analysis validated the RSI concept using Long-Term Pavement Performance (LTPP) Program data and the mechanistic-empirical pavement analysis software developed by the California Department of Transportation (CalME) to show functionality and what can be achieved at the network and strategic levels through the RSI concept.(5) As a result, this report documents the application of the process at the project, network, and strategic levels.

The approach for validating the RSI evolved throughout this project, as is described in this report. Initially, an RSI algorithm was developed and then data and models were pursued at the network level from State transportation departments and at the strategic level using the HPMS and PHT analysis tool. However, as is discussed in chapters 2 and 3, this validation approach required revision. For example, it was found that the available models at the strategic level did not support the validation approach (see chapter 3). In addition, the project-level evaluation, which is detailed in chapter 4, was included in an effort to show more specific applications of the RSI. Finally, the initial validation approach at the network level expanded from the threshold-driven approach described in chapter 2 to an optimization approach that is detailed in chapter 5.

REPORT ORGANIZATION

This report is organized into the following six chapters:

- Chapter 1 provides background information, details the project objectives, summarizes the project approach, and presents the report organization.
- Chapter 2 details the initial RSI algorithm developed for use in the validation efforts as well as the selection of the State transportation departments to be used in the validation effort. The network-level algorithm presented in chapter 2 represents the constrained approach initially used by the project team due to the limitations of the available models.
- Chapter 3 provides a summary of the validation analysis process at the project level using LTPP Program data, at the network level within State transportation departments, and at the strategic level using HPMS 2010+ data and the PHT analysis tool.
- Chapter 4 presents the project-level validation analysis using LTPP data.
- Chapter 5 presents the network-level validation analysis using data from the Maryland State Highway Administration (MDSHA).
- Chapter 6 presents a project summary as well as the major conclusions and recommendations that resulted from the project.

CHAPTER 2. RSI ALGORITHM AND AGENCY SELECTION

INTRODUCTION

This chapter documents the algorithms and methodologies formulated to perform the RSI application and validation analysis at the project level, the network level for two selected State transportation departments, and the strategic level using the PHT analysis tool. This chapter also documents the collection and review of information pursued to select two State transportation departments with good PMS practices to provide data in support of the validation analysis and actively participate in the project.

The development of the initial detailed analysis methodologies to implement the RSI concept at the project, network, and strategic levels are also detailed in this chapter. In development of these methodologies, the project team expected to use existing agency construction triggers, threshold limits, and performance prediction models as the basis for the computation of the RSI numerics. The methodologies presented in this chapter are general in nature so that they are applicable to both agencies and the PHT analysis tool.

At the onset of the project, the RSI concept was to take into account the lifecycle cost (LCC) of the pavement system based on determining the RSI numerics of preservation, rehabilitation, and reconstruction as a function of agency thresholds for providing an acceptable level of service (LOS) and construction triggers. More specifically, the RSI concept was to be validated within the LCC framework to create a consistent construction event-based terminology and understanding (i.e., types of construction events and the timing of those events within the LCC concept, risk analyses, and other prioritization approaches based on streams of future construction events and benefits to facility users).

While refining the general computation algorithms presented in this chapter, the RSI validation approach evolved from simply demonstrating the RSI concept within existing PMSs to demonstrating the concept within an "ideal" PMS where decisionmaking considers the optimal treatment selection, not based on thresholds, but considering all possible treatments and treatment timings to select the optimal timing for treatment selection while maintaining an acceptable or above an acceptable LOS based on agency specifications.

As the project progressed, benefits to using the optimum timing when applying a treatment (i.e., preservation, rehabilitation, or reconstruction) to better represent the ideal PMS and better support performance management arose, and, as a result, optimum timing was used within the RSI validation methodology instead of thresholds. This evolved approach is demonstrated in chapters 4 and 5.

PROJECT-LEVEL ALGORITHMS USING LTPP DATA AND CalME

The project-level validation objective was to demonstrate how the inclusion of structural measurements in the selection of rehabilitation strategies is beneficial in selecting the optimal treatment sequence to yield the LLCC for a given pavement section. Project-level validation compared five different treatment scenarios based on CalME analysis, which determined the performance extension of the pavement for each treatment based on its structural and functional condition at the time of analysis. The equivalent uniform annual cost (EUAC) for each treatment was determined after taking into consideration what would be required to bring the pavement to a state of good repair in order to select the optimal treatment based on LCC considerations. The Secretary of Transportation defined a *state of good repair* as "a condition in which the existing physical assets, both individually and as a system (1) are functioning as designed within their useful service life, (2) are sustained through regular maintenance and replacement programs"[(6)] (p. 2). The approach used in the project-level validation is detailed in chapter 4.

NETWORK-LEVEL ANALYSIS ALGORITHMS FOR STATE TRANSPORTATION DEPARTMENT PMSs

The initial approach to the network-level validation was to formulate a methodology for simulating the functionality of State transportation department PMSs over a 30- to 40-year analysis period based on the respective agency models. This goal would be accomplished by developing computer algorithms that mimicked pavement condition forecasting processes and the application of only LOS-based threshold limits using State transportation department procedures that produced LLCC. This process would theoretically generate a complete stream of future construction events for a network that the RSI numerics could be based on.

The 30- to 40-year analysis period was selected in order to show the long-range outcome of the network using combinations of preservation, rehabilitation, and reconstruction treatments in order to formulate the RSI numerics, which reflect the optimal treatments for LLCC. The extended analysis period was required to provide enough time for the optimal string of treatments to be selected in order to produce the LLCC.

Data and Pavement Performance Models

The network validation was to use State transportation department PMS information for the purpose of validating the RSI concept, including the following:

- Pavement condition and performance models (e.g., International Roughness Index (IRI), cracking, rutting, friction, and composite indices).
- Pavement condition threshold values used to trigger construction events, when identifying optimum time for the treatment is not possible due to lack of data or performance models.
- Construction cost information.
- Decision trees (e.g., what treatments are applicable based on condition or functional class).
- Rules, if any, applied within the State transportation department PMS (i.e., pavement sections with inadequate skid resistance are prioritized first prior to optimization due to safety concerns, etc.).

- Treatment benefits (e.g., if preservation treatment is placed when IRI = 120 inches/mi, what is IRI after treatment?).

No changes to the State transportation department PMS data or models were to be made in support of the RSI validation analysis effort.

Construction Events

While agencies may have multiple types of preservation or rehabilitation treatments, for planning purposes, they can be and generally are grouped under broader categories. For this effort, construction events were limited to the following four options:

- Do nothing.
- Pavement preservation.
- Rehabilitation.
- Reconstruction.

This simplification of the treatments used by agencies was recommended during the initial development stage of the RSI validation analysis process. The details of the actual treatments used within each category were to be implemented during the evaluation stage for each agency and are presented in chapter 5.

RSI Network-Level Validation Process

This section describes the process that was to be used in the network-level analysis based on the available data, pavement performance models, and construction events. The process described in this chapter shows the methodology that was to be applied to State transportation department data. The actual application of this methodology is presented in chapter 5.

The fundamental network-level approach was to develop alternative construction time histories allowing for various combinations of construction events. For each pavement section in the network, the different combination of construction time histories was determined based on the timing of each construction event, which could be threshold-driven or based on optimum timing and the improvement of the pavement condition as a function of the treatment timing. The pavement deterioration process then proceeded until the next construction event was triggered or applied. This process was continued until the pavement section under analysis reached the end of the analysis period.

A partial illustration of the hypothetical options that could result for a section in question is provided in table 1. A total of eight alternative construction time history options are shown. Each option shown in the top row is the combination of time history construction events shown in the subsequent column cells by year. Different road segments can have a different mixture of time history construction events to be evaluated. Once all the options were identified for a section, the optimal option was selected based on the LLCC.

Table 1. Possible combinations of time series construction events.

Year	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
1								
2								
3	Preservation	Preservation	Preservation					
4								
5								
6	Preservation							
7								
8								
9				Rehab	Rehab	Rehab		
10								
11								
12	Rehab							
13								
14								
15		Rehab		Preservation			Recon	Recon
16								
17								
18	Preservation			Preservation				
19								
20								
21	Preservation	Preservation			Rehab		Preservation	
22								
23			Recon					
24		Preservation					Preservation	
25								
26	Rehab			Rehab		Recon		
27					Preservation			
28								
29								
30		Rehabilitation	Preservation		Preservation		Rehab	

Blank cell = Year where no construction event occurs.

This shows that the section can be treated at different times with various treatments. Preservation can be placed early, or reconstruction can be delayed to later years. It is important that the LLCC for the section is used to determine the optimal treatment when comparing these alternatives.

Analysis Outputs

Ultimately, the outputs for the network analyzed (based on optimal option for each segment) are shown in table 2 and table 3. Table 2 shows the RSI numerics for each segment. For example, for segment 1, the RSI numerics are preservation treatments in years 3 and 5, followed by a rehabilitation in year 18, and then preservation in year 22. A similar RSI was calculated for each segment. Table 3 illustrates the costs associated with the RSI numerics outputs from table 2 for all segments in the network. It should be noted that table 2 only shows a sample of the RSI output and not the entire network. For example, the total cost for year 1 were $1,240,000, $24,355,000, and $5,546,000 for preservation, rehabilitation, and reconstruction, respectively.

Table 2. Sample RSI algorithm output.

Network Segment	RSI (Preservation) (years)	RSI (Rehabilitation) (years)	RSI (Reconstruction) (years)
1	3, 5, and 22	18	
2	8 and 24	5 and 20	
3	5, 7, and 30	2	25
X	11 and 13	26	6

X = Other network segments.
Blank cell = No reconstruction occurs.

Table 3. RSI output cost.

Year	Cost (Preservation)	Cost (Rehabilitation)	Cost (Reconstruction)	Total Cost
1	$1,240,000	$24,355,000	$5,546,000	$31,141,000
2	$2,650,000	$12,122,000	$12,980,000	$27,752,000
3	$590,000	$8,456,000	$20,456,000	$29,502,000
X	$3,234,000	$12,466,000	$4,234,000	$19,934,000

X = Future years.

STATE TRANSPORTATION DEPARTMENT SELECTION FOR NETWORK-LEVEL VALIDATION

For network-level validation, two State transportation departments needed to actively participate in the project. A list of seven potential State transportation departments was developed along with the reason for these recommendations. The seven potential State transportation departments included the following:

- Colorado.
- Maryland.
- Michigan.
- Minnesota.
- North Carolina.
- Virginia.
- Washington.

The following criteria were used to evaluate the potential State transportation departments:

- Has an interest in participating in the study.
- Has developed construction triggers, threshold limits, performance curves, and strategy selection algorithms that can be used to develop RSI numerics.
- Would provide details on algorithms used to perform processes previously described in the RSI Network-Level Validation Process section.

- Would provide PMS data and PMS outputs.
- Would appoint a project liaison and will meet with the project team at least twice.

A summary of each potential State transportation department follows along with a summary of the selection of two agencies based on a comparison to the previously listed criteria and their suitability for participation in the project.

Colorado Department of Transportation (CDOT)

CDOT previously used the RSL concept as a measure of the State's pavement quality. [7] However, in 2013, due to issues with the RSL-based system, CDOT implemented the drivability life (DL) analysis. The DL analysis aims to maximize acceptable driving conditions across the network and is a function of smoothness, pavement distress, and safety based on IRI, cracking, and rut depth data.

DL represents how long a highway will have acceptable driving conditions. The DL scale used by CDOT is as follows[7]:

- **High DL:** > 10 years.
- **Moderate DL:** 3–10 years.
- **Low DL:** ≤ 2 years.

CDOT uses the infrastructure asset management software to generate a list of resurfacing recommendations or strategies.[8] This software determines the recommendations by optimizing the incremental benefit-cost ratio (BCR) to maximize the benefit for the network for the given budget.[8] CDOT's goal is to have 70 percent of the resurfacing projects match the recommendations from the PMS. They are currently at 76 percent.[9]

MDSHA

In 1997, MDSHA began developing and implementing a pavement management approach based on optimization. During an enhancement of the pavement management practices, MDSHA combined probabilistic and deterministic models for use in forecasting and planning analyses at the network and project levels, respectively.[10] The probabilistic models were derived based on performance distributions for treatments, which were then used to develop the deterministic models in the form of performance curves.[10]

MDSHA also promotes a pavement preservation mentality. The pavement preservation program is based on a 6-year transportation program and relies on the PMS to develop performance-based pavement preservation plans.[11] MDSHA has developed a *Pavement Preservation Guide* that helps in the selection of the correct treatment through use of flowcharts, decision trees, and treatment tables.[12] Through the use of this guide, a series of treatment options can be determined for further consideration using more specific project information.[12]

The core processes of the pavement management program are performance monitoring, model development, network optimization, project selection, funding approval, pavement design, and construction and maintenance.[11] MDSHA PMS services include data collection, processing, analysis, and improvements to the PMS. These services use Web-based tools for network-level optimization and project-level selection using BCR and RSL.

MDSHA uses a PMS software to optimize their budget planning and project selection. The software includes optimization tools (BCR, remaining life, etc.), asset management, geographic information systems, an image viewer, data warehousing, and data viewer tools.

Michigan Department of Transportation (MDOT)

MDOT has a mature PMS that was developed in the 1980s. MDOT also emphasizes a pavement selection strategy developed in the 1990s that consists of rehabilitation and reconstruction (R&R), capital preventative maintenance (CPM), and reactive maintenance. CPM is used to manage pavements with an RSL greater than 2 years, and R&R is used for pavements with an RSL of less than 2 years.(13)

MDOT evaluates the condition of the pavement systems using both a sufficiency rating and a PMS rating. The sufficiency rating consists of an annual subjective windshield survey, while the PMS rating consists of detailed pavement condition data collected biennially.(13) Using the collected pavement condition data, such as cracking, raveling, flushing, spalling, faulting, roadway curvature, pavement grade, cross slopes, rutting, and ride quality, a Distress Index and a Ride Quality Index (RQI) are computed.(13) MDOT considers a pavement with an RSL of zero and an index value of 50 or greater to be in need of reconstruction or major rehabilitation.(13) MDOT has several performance measures for the trunkline (consisting of all State highways) network, including 90 percent of pavements in fair or good condition based on IRI according to FHWA standard and 90 percent of pavements having an RSL of 3 years or greater.(14,13)

MDOT uses the Road Quality Forecasting System (RQFS) to evaluate pavement strategies for both short- and long-term condition levels by predicting future pavement condition and determining funding needs to meet desired conditions.(13) The RQFS determines the percentage of the network that moves between RSL categories based on the suggested project selection and selects the strategy that is most effective and promotes a “preserve first” strategy.(15)

Minnesota Department of Transportation (MnDOT)

The MnDOT PMS contains an estimate of pavement RSL. As part of its annual report, the MnDOT Pavement Management Unit determines RSL for all highway segments. The RSL is determined as the number of years until an RQI of 2.5 is reached. The RQI is a smoothness index with a 0 to 5 scale; increasing values representing smoother roadways.

MnDOT implemented the Highway Pavement Management Application (HPMA) PMS in 1987.(16) MnDOT uses HPMA in supporting the decisionmaking process through performance models, decision trees, and treatment selection; however, the MnDOT districts have significant influence on the project selection with input from the Pavement Management Unit, making it decentralized.(16) The PMS considers preventative maintenance (crack seal/fill, rut fill, chip seal, thin non-structural overlay, concrete joint seal, and minor concrete repair), rehabilitation (medium overlay, thick overlay, medium mill and overlay, thick mill and overlay, and major concrete repair) or reconstruction (cold in-place recycling, rubblized portland cement concrete (PCC) and overlay, unbounded concrete overlay, and full-depth reclamation).(16) MnDOT uses the performance curves in HPMA to predict RSL based on RQI. The RSL and future pavement condition are used to provide information regarding the impact of various funding scenarios.[17]

North Carolina Department of Transportation (NCDOT)

NCDOT uses a transparent, systematic, and data-driven process for prioritizing the major transportation components in the State and making investment decisions. This process, developed in collaboration with key partners, evaluates the benefits the project is expected to provide, the project's multimodal characteristics, and how the project fits in with local priorities. NCDOT's first Strategic Prioritization Process (known as Prioritization 1.0) was implemented in 2009 and was subsequently codified into law in 2012.[18] NCDOT implemented the third generation of the Strategic Prioritization Process in 2014. NCDOT has also developed the Interstate Maintenance Preservation Program, a rating system for application of pavement preservation treatments that is unique and could be investigated with the RSI concept.

NCDOT's PMS inputs the condition database, decisions trees, and performance models and then uses a multiobjective, multicriteria optimization analysis to output project-level lifecycle reports, network-level investments and funding strategies, forecasted conditions at the network and project levels, and comparative analyses of investment strategies.[19]

Virginia Department of Transportation (VDOT)

VDOT has a mature PMS that was developed in the 1980s. Currently, it uses the Critical Condition Index (CCI) to categorize pavement condition. VDOT aggregates pavement condition data collected by their vendors into load-related distress ratings (LDRs) and non-load-related distress ratings (NDRs). The lower of these two ratings is taken as the CCI. NDR considers transverse and longitudinal cracking, longitudinal joint separation, bleeding, etc., and LDR considers distresses caused by vehicle loads such as fatigue cracking, patching, and rutting.[20] Pavement condition is assigned according to the CCI value ranging from excellent to very poor, with a CCI rating of 60 or greater representing sufficient condition.[20] The statewide target is for 82 percent of interstates to be rated as sufficient. (As of 2012, 82.9 percent of interstates were rated as sufficient.[20]) VDOT also evaluates pavements based on IRI. Pavements are considered deficient in terms of ride quality if the IRI is 140 inches/mi or greater for interstates and primary roads or 220 inches/mi for secondary roads.[20] The statewide target is to have 85 percent of interstates with sufficient ride quality. (As of 2012, 93.3 percent of interstates have sufficient ride quality.[20])

VDOT implemented a new PMS in 2010 with features such as analysis of current pavement conditions, pavement performance modeling and forecasting, and calculation of performance-based needs expectations.[21] The PMS also includes a multiyear optimization strategy selection tool, which considers the maintenance alternatives of do nothing, preventative maintenance, corrective maintenance, restorative maintenance, and major rehabilitation/reconstruction.[21] The network-level analysis can base the optimization on maximizing the benefit, maximizing the condition indicator, or minimizing the total cost as a function of treatment costs or desired condition level.[21]

Washington State Department of Transportation (WSDOT)

WSDOT has a mature PMS, which was developed in the 1970s and fully implemented in 1982. It is considered a national leader in the field.[22] Based on the collected pavement distress data, WSDOT assigns three different pavement condition indices—pavement structural condition (PSC), pavement rutting condition (PRC), and pavement profile condition (PPC)—on a scale of 0 to 100, where 0 represents extensive distress and 100 represents a pavement with no distresses.[22] Using the PMS and performance curves, WSDOT projects when any one of the condition indices will reach 50 and determines the ideal time for rehabilitation using LLCC and other techniques to select optimum pavement construction strategies within a 6-year investment program.[22] Through this process, WSDOT promotes pavement preservation.

WSDOT uses WebWSPMS as the principle application for their pavement asset management. The Web-based WebWSPMS, which was developed in-house, provides an interface for accessing and viewing data from several sources including roadway configuration, location information, contract history, traffic information, capital projects, pavement activities completed by maintenance, construction contract costs and milestones, condition information, imagery, and data synthesis and analysis.

Agency Selection

Using the criteria set out at the beginning of the State Transportation Department Selection for Network-Level Validation section and the summary of the agencies provided, MDSHA and WSDOT were selected for participation in the study. Both agencies had developed construction triggers, threshold limits, performance curves, and strategy selection algorithms and used the RSL concept. In addition, both agencies were willing to provide details for the strategy selection algorithms and access to their PMS data and PMS outputs and to work with the project team to meet the objectives of the project.

STRATEGIC-LEVEL ANALYSIS ALGORITHMS FOR PHT ANALYSIS TOOL

In addition to project- and network-level validations, the proposed RSI concept was to be validated at the strategic level using FHWA's PHT analysis tool. However, as detailed in chapter 3, the models implemented into the current version of the PHT analysis tool did not support the validation of the RSI. The PHT analysis tool estimates pavement RSL for highway sections based on data items described in the 2010 revision of the HPMS database maintained by the FHWA.[23] The PHT analysis tool quantifies the RSL of the pavement for each highway section using the simplified American Associations of State and Highway Transportation Officials (AASHTO) *Mechanistic-Empirical Pavement Design Guide* (MEPDG) based performance prediction models.[24] The RSL is the number of years, or equivalent single-axle loads, remaining until pavement distress reaches a level where action is warranted.[4]

Proposed Algorithm for the Strategic-Level Validation

The validation of the RSI at the strategic level included adding an RSI module to enhance the PHT analysis tool. The RSI module was proposed to be developed as a plug-in to be integrated with the PHT analysis tool. The RSI module used the simplified pavement performance models

(IRI, cracking, etc.) contained in the PHT analysis tool, which were based on the MEPDG.[(24)] No changes to the PHT analysis tool performance models were made.

The RSI module was designed so that for a given set of HPMS 2010+ data, analysis period, and minimum LOS to be maintained in addition to other constraints currently included in the PHT analysis tool, it provided a list of lifecycle cost analysis (LCCA) optimized series of treatments, timing, and costs for each pavement section over the analysis period. The remainder of this section will provide details of the algorithm used.

Setup and Rules

The proposed strategic level RSI algorithm was to consider the following four types of construction events:

- Do nothing.
- Pavement preservation.
- Rehabilitation.
- Reconstruction.

Each construction event had a threshold limit, which increased from preservation to reconstruction (i.e., the threshold limit of percent cracking increases from 15 to 25 percent from preservation to reconstruction). For example, table 4 from the Pavement Remaining Service Interval Implementation Guidelines can be used to define the threshold limits for reflection cracking or the IRI.[(25)]

Table 4. Threshold limits for construction events.

Construction Events	Reflection Cracking (percent)	IRI (inches/mi)
Do nothing	No cracking	< 90
Pavement Preservation	< 15	90 to 150
Rehabilitation	15 to 25	150 to 250
Reconstruction	> 25	> 250

Each of these construction events also costs more to implement, with preservation being the least costly and reconstruction being the most costly. The algorithm was to abide by the following rules when considering the construction events:

- More than two successive preservation treatments were not allowed. Although this is an acceptable practice by many agencies and is often used, this rule was implemented to limit the choices for illustration purposes.

- Only one rehabilitation event within a 10-year period was allowed.

- Only one reconstruction event within a 20-year period was allowed.

Calculation of LLCC

In order to calculate the LLCC for a given highway section, the algorithm was to operate as follows:

1. For each pavement section, use PHT analysis tool prediction models to calculate the year when a pavement preservation, rehabilitation, or reconstruction treatment was needed based on the set thresholds. A threshold-driven approach was used because modification of the PHT analysis tool to fully incorporate an LCC-based approach was not feasible at the time of this project.

2. Create two construction scenarios (apply treatment from step 1 or do nothing) while considering the rules stated in the setup and rules.

3. For each construction scenario, determine associated construction costs and year when next construction event is triggered.

4. If the analysis period has not been reached, update model inputs and go back to step 1.

5. If the analysis period has been reached, consider all scenarios and find LLCC option for highway section.

6. Record LLCC option (year of treatments and costs) for the highway section and repeat steps 1 through 5 for other highway sections in network.

Figure 3 shows a flowchart highlighting the algorithm's operation. The flowchart shows that for an available highway section, the prediction models are used to identify a year that triggers a construction event. If the analysis period is not yet met at that year, then two scenarios are considered: do nothing or apply treatment. This cycle is continued until the analysis period is reached for each highway section. The lowest LCC option from all possible scenarios is then selected and added to the summary table.

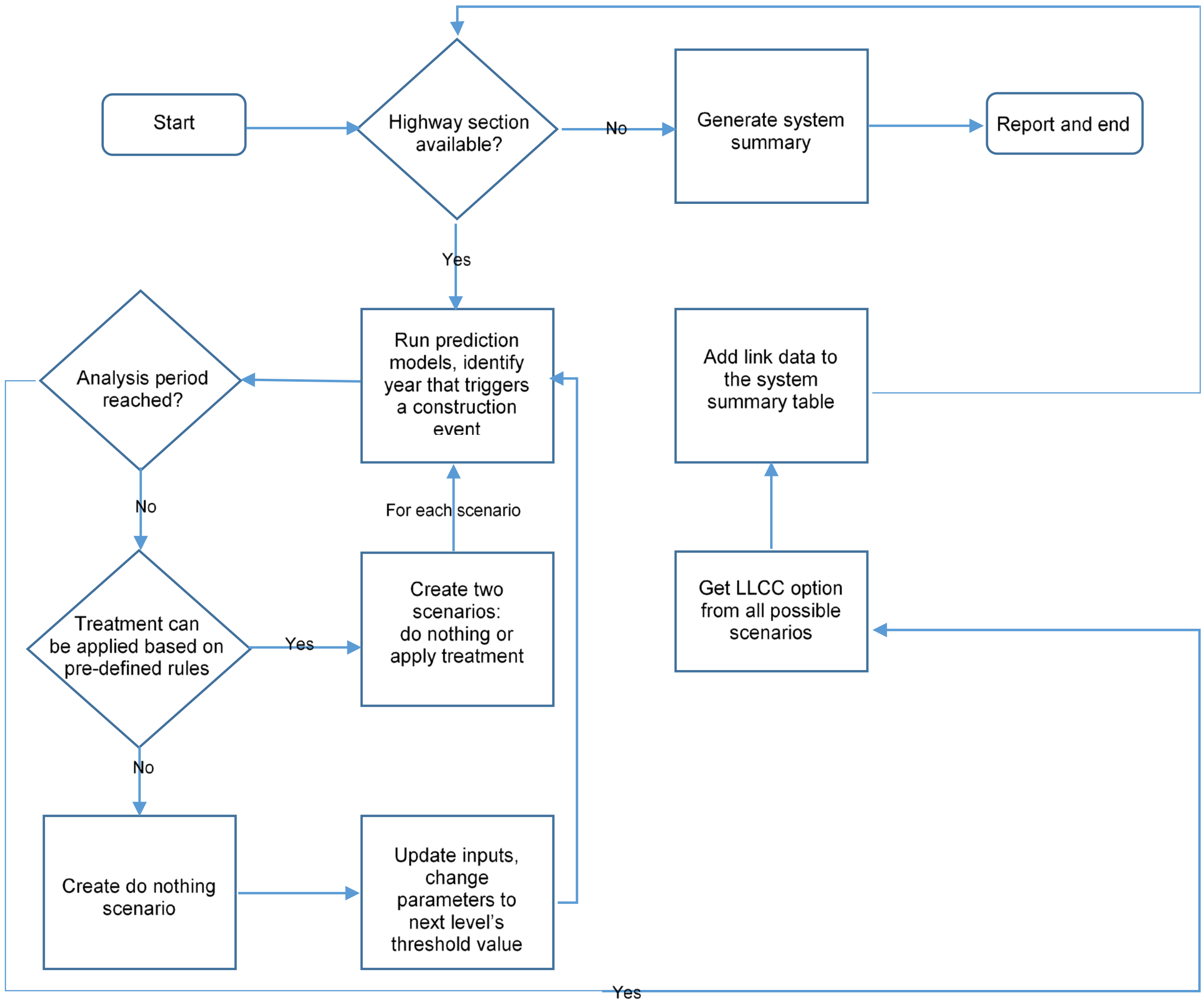


Figure 3. Flowchart. Proposed RSI algorithm.

Implementation Strategy

The PHT analysis tool has the capability to import HPMS 2010+ data. The PHT analysis tool pavement deterioration models are simplified MEPDG models similar to those developed for the Highway Economics Requirements System (HERS).[26] By using the PHT analysis tool, the proposed RSI algorithm's implementation reused the input and prediction models steps of the basic RSL process in the PHT analysis tool. The proposed RSI implementation, therefore, focused on the strategy selections step of the RSI module while allowing PHT to take care of the input and the prediction model steps.

The following list includes the data requirements for the PHT analysis tool and the RSI algorithm from HPMS 2010+ data:

- AADT.[1]
- AADT_Combination.
- AADT_Single_Unit.
- Base_Thickness.
- Base_Type.
- Begin_Point.
- Climate_Zone.
- County_Code.
- Cracking_Length.
- Cracking_Percent.
- End_Point.
- Expansion_Factor.
- Facility_Type.
- Faulting.
- F_System.[2]
- Future_AADT.
- Future_AADT_Year.
- IRI.
- Lane_Width.
- Last_Overlay_Thickness.
- NHS.[3]
- PSR.[4]
- Route_ID.
- Rutting.
- Shoulder_Type.
- Soil_Type.
- Speed_Limit.
- State_Code.
- Structure_Type.
- Surface_Type.
- Thickness_Flexible.
- Thickness_Rigid.
- Through_Lanes.
- Urban_Code.
- Volume_Group.
- Year_Last_Construction.
- Year_Last_Improv.
- Year_Record.

The PHT analysis tool is sensitive to these data inputs. Performing analysis using the PHT analysis tool on pavement sections that are missing these data inputs is not recommended.

[1]Average annual daily traffic.
[2]Functional system.
[3]National Highway System.
[4]Pavement serviceability rating.

As part of the PHT analysis, the input data were validated. If input data were missing from the HPMS data, it was possible to supplement the data from other sources if available. Sections that did not contain the required data or other requirements were removed from the analysis.

SUMMARY

This chapter documented the algorithms formulated to perform the RSI application and validation at the project level, the network level for two selected State transportation departments, and the strategic level using the PHT analysis tool to demonstrate the RSI concept.

Chapters 3, 4, and 5 describe how the RSI concept evolved beyond considering the whole life of the pavement system as illustrated by the algorithms documented in this chapter to further considering and determining the optimal decision for the pavement system. Instead of determining the RSI numerics of preservation, rehabilitation, and reconstruction RSI based on the construction thresholds, the RSI numerics would be established by the optimal timing of treatments in order to produce the LLCC for the pavement system. This evolution represents a shift from a change in terminology, as was initially presented, to a change in approach. The details of this evolution are presented in chapters 3, 4, and 5.

CHAPTER 3. APPLICATION AND VALIDATION OF RSI FRAMEWORK AT PROJECT, NETWORK, AND STRATEGIC LEVELS

INTRODUCTION

This chapter provides an overview of the application and validation of the RSI framework at the project, network, and strategic levels. It documents the efforts under each level, including the initial processes and data used in the validation. In addition, limitations with available data and models that caused the project team to stop pursuing the validation using WSDOT are presented in this chapter. Finally, this chapter documents the issues encountered when the validation was pursued using the FHWA PHT analysis tool and presents some recommendations on how to address them.

PROJECT-LEVEL VALIDATION APPROACH

The approach to validating the RSI at the project level consisted of developing optimal treatment strategies for a given pavement section over a defined time frame using mechanistic-empirical models. The basic algorithm used in the project-level validation is illustrated in figure 4. The RSI is the string of numbers that represent the optimum treatment sequence.

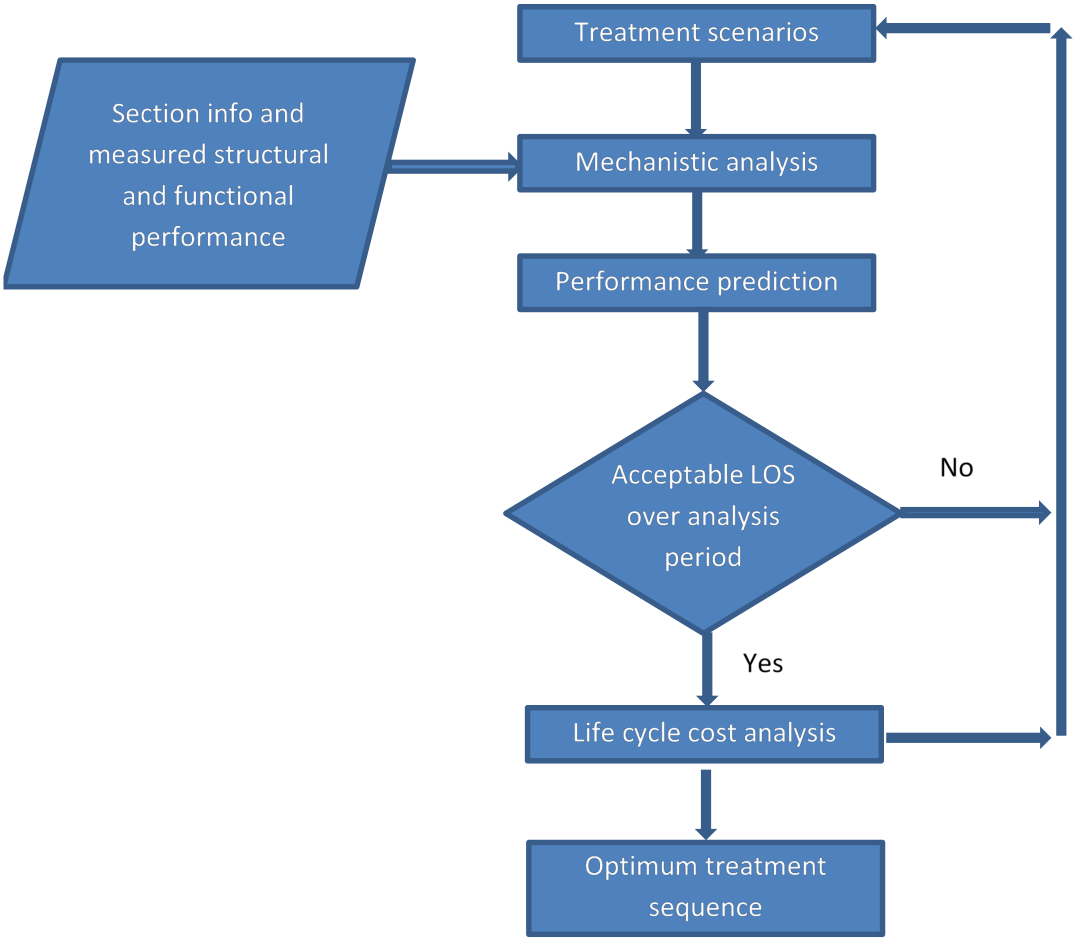


Figure 4. Flowchart. Project-level analysis.

Project-level analysis requires more detailed data because it includes pavement design and performance modeling specific to the project location. For this effort, LTPP data were used. The project-specific data and treatment scenarios were used as input for CalME in order to predict performance. If the performance prediction resulted in acceptable or above acceptable LOS over the analysis period, the performance prediction and the structural condition were used as inputs for the LCCA. If the LOS needs were not met, the treatment scenarios were revised. This allowed for the identification of the optimum treatment sequence as well as quantification of potential monetary loss of delaying the optimum treatment.

NETWORK-LEVEL VALIDATION APPROACH

The overall goal of the network-level validation was to further develop the application of the RSI concept using real-world data from two State PMSs. As documented in chapter 2, MDSHA and WSDOT were selected for this validation. This section details the efforts undertaken as part of the network-level validation with these agencies.

MDSHA

For pavement management, MDSHA uses pavement condition and two cracking indices: a Functional Cracking Index (FCI) that combines functional cracks on a scale of 0 (worst) to 100 (best) and a Structural Cracking Index (SCI) that combines structural cracking on a similar 0 to 100 scale. MDSHA uses PMS software as a pavement management decision support tool that includes project selection optimization capabilities as well as value assessments in developing maintenance needs. The PMS software uses a remaining life/cost optimization process.

MDSHA employs a biennial approach to project selection optimization. The optimization uses RSL categories within the PMS software, where there are budgets and benefits for maintenance, preservation, and rehabilitation. The PMS software optimization is based on roughness and cracking. The optimization takes into account the weighted vehicle-miles traveled (VMT) in reaching the targets set as well as in determining the percent poor and percent with zero life, known as deficients. The objective function used in the optimization is presented in chapter 5.

The optimization steps include the following:

1. Import committed projects into “ride and crack” simulation.
2. Analyze bonded PCC overlay.
3. Perform targets/deficients-met run in “ride and crack” simulation.
4. Perform no-spending run in “all condition” simulation.
5. Run queries, segment, and roll up “friction and skid” network.
6. Perform as-budget permits run in “friction and skid list” simulation.
7. Perform targets/deficients run for all years in “ride and crack” simulation.
8. Perform no-spending analysis in “all condition” simulation.
9. Generate reports.

Validation Effort

The initial approach to validating the RSI using MDSHA data, models, and business processes was to modify the PMS software in order to implement multiyear optimization. More specifically, the PMS software needed to be expanded to accommodate the 30- to 40-year analysis period required for the RSI validation. Several modification options were developed, including the following:

- Implement a basic multiyear optimization analysis similar to the existing single-year optimization and selection of a single treatment.

- Recalculation of feasible projects in the out years in addition to the projects selected in the current process.

- Evaluate all feasible paths available for a section considering multiple treatments as a single treatment for selection purposes. For example, the following plan would qualify as a single treatment:

  - **Chip seal:** year 1.

  - **Crack seal:** year 3.

  - **Overlay:** year 5.

  A BCR would be determined for the entire plan, which would be ranked against other possible plans.

Since the RSI concept was to consider the optimal treatment selection based on all possible treatments while maintaining an acceptable or above acceptable LOS, none of the previous options provided the required functionality needed for the RSI validation. Specifically, these modifications would not allow for true optimization based on all possible treatments and treatment timings. Thus, modification to the PMS software was not pursued through to implementation.

The second approach to validating the RSI using MDSHA data, models, and business rules was to independently develop a program for selecting optimal strategies. As a result, a brute force approach to simulating the modeling of the software was proposed. To support this effort, decision trees, treatment types, treatment benefits, treatment feasibility, performance models, conditions, and cost data were obtained from MDSHA. The MDSHA PMS has 35 treatments within the decision tree ranging from preservation to reconstruction. The PMS also considers 7 friction models for various functional classes, 48 cracking models for both FCI and SCI, 35 IRI models for combination of region and functional class, and 3 rutting models for groups of functional class.

As a result of the number of models and treatments, in an effort to make the brute force approach feasible, only asphalt pavement was considered. A spreadsheet containing the required information (condition data, performance models, treatment benefits and feasibility, and cost) was prepared. However, once compiled, it was apparent that the requirements to complete to optimization with the MDSHA data were beyond the capabilities of the spreadsheet program. In order to truly implement the RSI algorithm as it had evolved to consider all possible treatments and treatment timings and not only those based on thresholds, multiple global optimization procedures were adopted and enhanced for use with MDSHA. The details of this validation effort are presented in chapter 5.

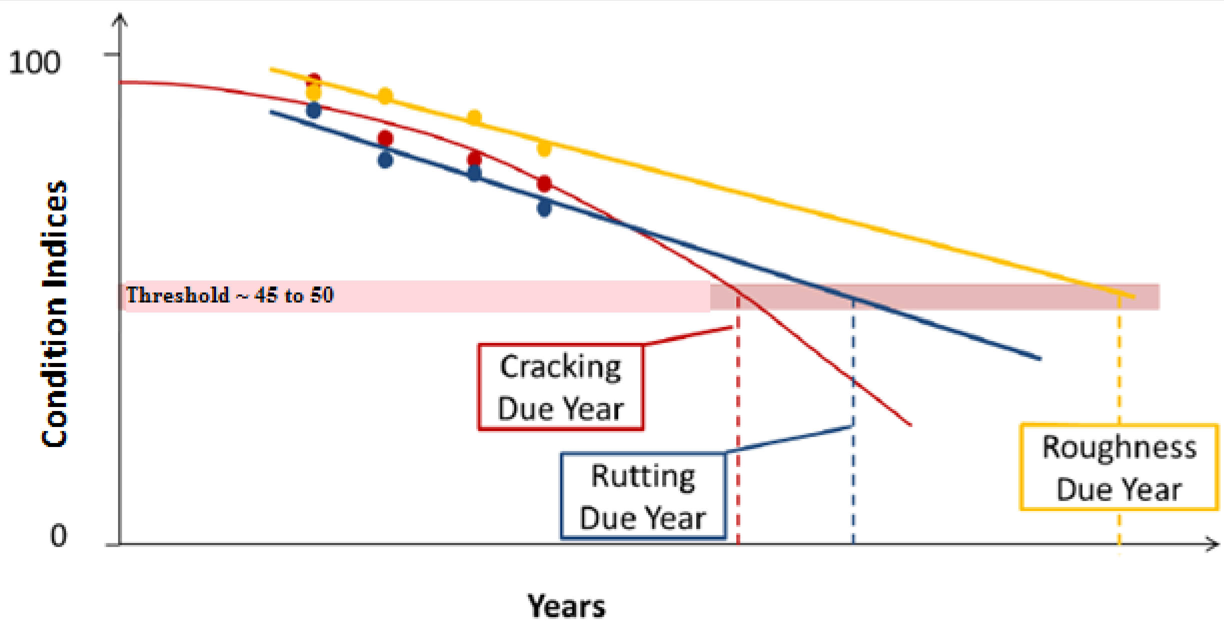
WSDOT

For pavement management, WSDOT uses distresses and pavement condition indices. The indices range from 0 (very poor) to 100 (very good) and identified the need for treatment action when any index value reaches 45 to 50. The typical treatment used by WSDOT is a 0.15-ft overlay or inlay. The indices for asphalt pavements are as follows:

- **PSC:** Assesses the structural health of the pavement based on cracking and patching present. The input is equivalent cracking, and the model is a power function.
- **PPC:** Assesses the roughness of the road. The input is IRI, and the model is linear.
- **PRC:** Assesses the rutting of the road. The input is rutting, and the model is linear.

Performance Forecasting

Within the Washington State PMS (WSPMS), the pavement indices prediction equations are updated over time using a time series regression analysis in order to tailor the performance curve to observed pavement conditions. As depicted in figure 5, the coefficients in the default series of family pavement performance prediction models are adjusted using a least squares algorithm based on field reported time series observations. In figure 5, the solid lines illustrate the default family of performance prediction curves, which are subsequently updated using field observations shown as the series of times series dots on each curve. While the default performance prediction curves provide a baseline estimate at the start of each new performance cycle, the adjustment of the prediction curves with observed field data over time provides a higher degree of confidence in the predicted results of the future performance predictions of specific pavement sections.



Source: WSDOT.

Figure 5. Graph. WSDOT curve fitting.[27]

The other concept of interest to this investigation is the “due year” terminology shown in figure 5. The due year is the predicted time that one of the indices will reach the threshold value of 45 to 50, at which point the next treatment is due.

Validation Effort

The RSI concept has many facets. While there is focus on nomenclature, other aspects of the concepts include use of LCCA as a basis for cost optimization approaches. It was postulated that optimum treatment times could be derived from LCCA. Within the LCCA concept, thresholds of acceptable LOS are still used.

Condition Index Thresholds: In order to demonstrate the RSI concept, the project team was interested in quantifying the benefits of applying treatments at different pavement conditions instead of fixed threshold values in order to identify optimum timing for preservation, rehabilitation, and possibly reconstruction for each pavement section (survey unit) in the network. This was based on the reasoning that the treatment effectiveness and posttreatment benefits are a function of pretreatment pavement condition and that there may be an optimum pretreatment condition (or timing) that yields the maximum lifecycle cost benefits.

In discussion with WSDOT, it was determined that although treatment is triggered at an index range of 45 to 50, when the treatment is applied, pavement sections at various conditions are included in the project (referred as preservation units in WSPMS) when grouping several pavement sections together for a preservation unit. In other words, the index range of 45 to 50 corresponds to the average condition of the preservation unit within which there may be pavement sections with a range of conditions. As a result, within a project, there are pavement sections that are still in good condition and also pavement sections that are in fair to poor condition when a resurfacing treatment is placed. It was hypothesized that the pretreatment condition of the section will have an effect on the posttreatment performance of the treatment and the pavement as a whole. In order to investigate this hypothesis, data from the WSPMS were analyzed for asphalt pavements where resurfacing was triggered only by the PSC index.

The initial findings of the investigation showed no discernable relationship between the posttreatment performance of a treatment from the average performance and the pretreatment condition. Additional analyses were considered and conducted to identify possible reasons for the observed lack of correlation, including the following:

- Pavement survey units with asphalt concrete (AC) overlay thickness of 0.2 ft or more.
- Rehabilitation treatment of 0.15-ft mill and fill.
- Pavement survey units with posttreatment distress (PSC < 60) in 2013 WSPMS measurements. This was done so that the performance model curves were largely driven by the section performance rather than family (default) performance. Also, the effect of region was studied in this subgroup.

These additional analyses yielded a similar lack of correlation as the initial analysis, and the project team concluded that the data does not adequately reflect the effect of pretreatment condition on the AC overlay treatment performance as was expected.

Since the treatment mostly used by WSDOT is resurfacing (0.15 ft hot-mix asphalt (HMA) overlay or inlay), it was hypothesized that most of the measured cracks that affect the PSC are surface-initiated (top-down) cracks that have not damaged the integrity of the overall pavement structure. Therefore, by applying the rehabilitation treatment, the condition of the total project (all preservation units) is improved to a relatively uniform structural condition irrespective of the pretreatment condition.

Since it appears that most of the cracks are surface initiated, PSC does not fully capture the true structural condition of the pavement and it is more properly reflective of the pavement surface condition. The PSC also fluctuates once below 50 as a result of maintenance activities and its sensitivity to judgement calls for extent and severity of alligator cracking.[28] In addition, WSDOT staff explained that the power model is not reliable for communicating the actual pavement rehabilitation need past the point of resurfacing. Because of this, when forecasting assumptions are made, the number of years past due is used as an estimate of need for rehabilitation/reconstruction as opposed to following the power model or current PSC score. It may be that the surface condition alone can never approximate the true structural condition (past the point of resurfacing).

Finally, according to WSDOT staff, asphalt resurfacing was generally sufficiently funded during 1995–2005. As a result, asphalt roadways are rarely allowed to deteriorate to a point where significant rehabilitation or reconstruction costs were incurred.

Treatment Type Performance

The next consideration was given to investigating treatment performance, or time between treatments, for the various types of treatments of preservation, rehabilitation, and reconstruction. The objective was to identify whether there was a significant difference between the time between treatments for reconstruction, rehabilitation, and preservation. Based on the previous findings and the understanding that WSDOT pavements are generally considered to be structurally sound as well as knowledge of WSDOT practices (i.e., placing 0.15-ft resurfacing when index values reach between 45 and 50), significant differences in treatment life or time between treatments were not anticipated.

The analysis used the contracts table from the 2014 WSPMS research database to identify each treatment type under the contract type in the table. Reconstruction is directly identified as specified in the table. However, rehabilitation and preservation are not directly specified in the table because the contract type is listed as resurfacing. For the purpose of this analysis, preservation was considered as a resurfacing with thickness of 0.15 ft or less because this is a typical treatment applied by WSDOT. Rehabilitation was considered as a resurfacing with a thickness greater than 0.15 ft with an average of 0.36 ft for the sample. A small random sample of sections was analyzed. This sample only considered asphalt pavements and did not consider exceptions such as lane additions, widening, etc. The treatment life was determined as the average time between the treatment placement and the placement of next treatment of any type.

It should be noted that many of the sections that were classified as rehabilitation based on the thickness of the resurfacing either were originally concrete pavements or had previously had a chip seal surface treatment placed prior to the rehabilitation. Therefore, the rehabilitation sample size was smaller because these pavements were not included.

Table 5 provides the summary statistics for the treatment life, and figure 6 depicts a histogram of the performance life of the treatments. Although table 5 shows that the mean and median time between treatments is greatest for reconstruction and least for preservation, as would be expected, these difference are not statistically significant.

Table 5. Summary statistics of treatment life.

Treatment	Mean (years)	Median (years)	Standard Deviation
Reconstruction	18.2	17.4	7.1
Rehabilitation	14.7	16	4.2
Preservation	14.5	14	4.1

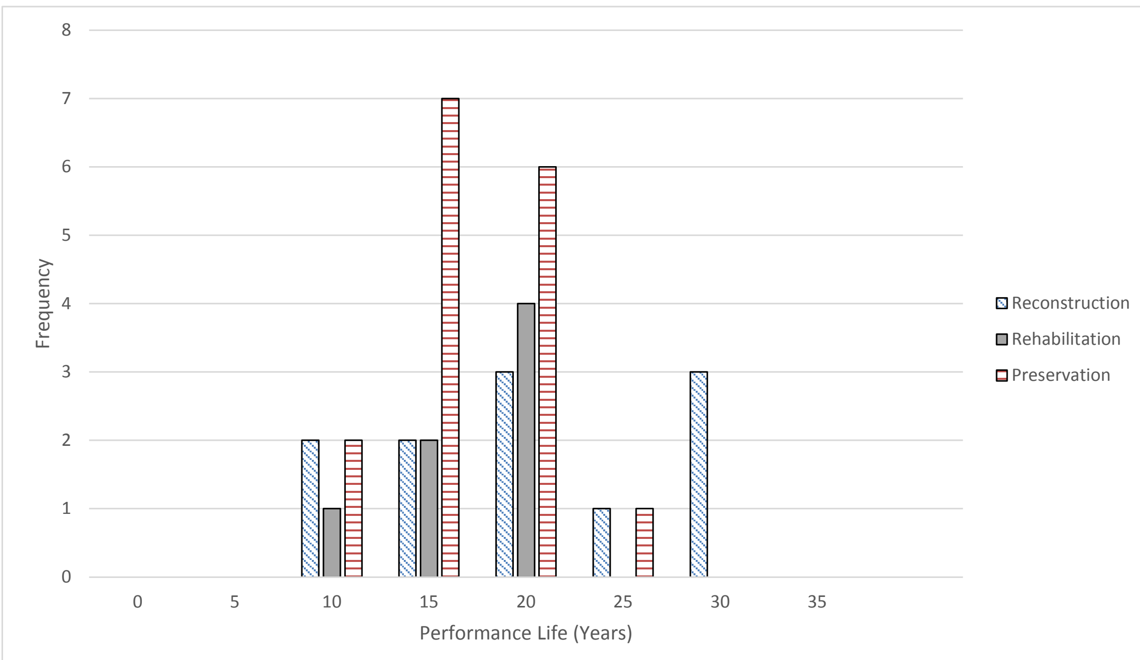


Figure 6. Histogram. Treatment life.

An analysis of variance (ANOVA) was performed on the three samples to determine whether the means were significantly different or not. Table 6 contains the ANOVA summary. Because the F statistic is less than the F-critical (F_{crit}) (and the p-value is greater than alpha = 0.05), there is not enough statistical evidence to suggest that the means of the treatments are different (fail to reject the null hypothesis that all means are equal), meaning that there is not a statistically significant difference.

Table 6. ANOVA summary.

Source	*SS*	*df*	*MS*	*F*	*p*-value	F_{crit}
Between groups	96.0	2	48.0	1.715	0.1965	3.305
Within groups	867.8	31	28.0			
Total	963.8	33				

df = Degrees of freedom.
MS = Mean square.
SS = Sum of squares.
Blank cell = Not applicable.

Conclusions from WSDOT Validation Effort

As a result of not being able to find either a correlation between pretreatment condition and treatment life or a significant difference between the performance life for the different treatments, the project team concluded that it would not be possible to validate the RSI concept using WSDOT data because the concept requires the use of a broader range of treatment options and trigger values.

This does not have negative connotations for WSDOT; on the contrary, it suggests that the agency has taken on a "pavement for life" approach in which pavements are repaired before the pavements have suffered significant structural damage. In addition, the project team found WSPMS to contain quality data, which aided in the analyses. The use of WebWSPMS was also easy to follow and beneficial in visualizing conditions and sections.

STRATEGIC-LEVEL VALIDATION APPROACH

The overall goal of the strategic-level validation was to demonstrate and further develop the application of the pavement RSI concept using the HPMS 2010+ dataset. This validation used the FHWA PHT analysis tool. The analysis algorithms documented in chapter 2 were implemented into the PHT analysis tool via an RSI module developed as part of the project.

PHT Analysis Tool and HPMS

The PHT analysis tool was developed under an effort by the FHWA Office of Asset Management, as documented in *PHT Analysis Tool, Summary Report*.[(29)] The current version of the tool is 2.0. The PHT analysis tool was developed to work with HPMS 2010+ data or appropriately formatted State transportation department PMS data to predict various pavement condition and health indices based on pavement structure data, current condition, past performance, and assumed actions. However, the PHT analysis tool was developed before the RSI concept; therefore, the RSI concept was not included in the PHT analysis tool.

The PHT analysis tool uses a multicondition approach to estimate pavement RSL. The first step evaluates the structural condition as the time until the pavement structural condition deteriorates to renewal intervention level (e.g., excessive alligator cracking, transverse cracking, rutting, and faulting). The second step evaluates the functional condition as the period after which the pavement no longer provides the required level of service or desirable user ride quality. The user can choose to report the pavement section RSL as the weighted average or minimum of the RSL from the previous two steps.

The pavement distress models included in the PHT analysis tool are simplified forms of pavement distress models (i.e., IRI, cracking, etc.) used in the AASHTO MEPDG, along with construction and rehabilitation/maintenance history.(24) The models also allow self-calibration if historical data items are available.

The PHT analysis tool uses HPMS 2010+ data as input data. The pavement distress models used in the PHT analysis tool are very sensitive to some pavement data inputs. Performing analysis using the PHT analysis tool on pavement sections that are missing these data inputs is not recommended. As part of the PHT analysis, the input data must be validated. Sections that do not contain the required data or other requirements should be removed from the analysis. Default MEPDG values for data items such as climate zone or soil type may be used based on a given state and county.(24) The following data elements are required by the PHT analysis tool, and the pavement data items that are mandatory for the PHT analysis tool are bolded:

- AADT.
- AADT_Combination.
- AADT_Single_Unit.
- **Base_Thickness**.
- **Base_Type**.
- Begin_Point.
- Climate_Zone.
- County_Code.
- Cracking_Length.
- Cracking_Percent.
- End_Point.
- Expansion_Factor.
- Facility_Type.
- Faulting.
- F_System.
- Future_AADT.
- Future_AADT_Year.
- IRI.
- Lane_Width.
- **Last_Overlay_Thickness**.
- NHS.
- PSR.
- Route_ID.
- Rutting.
- Shoulder_Type.
- Soil_Type.
- Speed_Limit.
- State_Code.
- Structure_Type.
- **Surface_Type**.
- **Thickness_Flexible**.

- **Thickness_Rigid**.
- Through_Lanes.
- Urban_Code.
- Volume_Group.
- **Year_Last_Construction**.
- **Year_Last_Improv**.
- Year_Record.

As part of this project, enhancement of the PHT analysis tool to incorporate the RSI concept was pursued for use in the validation of the RSI framework with HPMS 2010+ data for national-level application. The remainder of this section provides an overview of the PHT analysis tool using HPMS 2010+ data, development of the RSI module, the validation effort using the RSI module, and findings and conclusions.

Validation Effort

The RSI module was developed under this project as a plug-in that was integrated with the PHT analysis tool for use with HPMS 2010+ data for the computation of RSI. The RSI module was to use the simplified MEPDG derived pavement performance models contained in the PHT analysis tool. No changes to the PHT analysis tool performance models were made.

The RSI module was designed and developed to provide a list of LCC optimized series of treatment, timing, and cost for each pavement section over the analysis period. The RSI module required inputs data such as HPMS 2010+ pavement sections, related data, analysis period, and minimum LOS to be maintained in addition to other constraints currently included in the PHT analysis tool. A threshold-based approach was used to trigger construction events because identification of optimum treatment timing required modifying the PHT analysis tool, which was not feasible at the time of this project.

Development of RSI Module

For the development of the RSI module, an RSI algorithm considering construction events and threshold limits, rules, and calculation of LCC was developed. The proposed RSI algorithm was to consider the following four types of construction events:

- Do nothing.
- Pavement preservation.
- Rehabilitation.
- Reconstruction.

The RSI analysis sets the threshold limits for the pavement distresses used by the PHT analysis to levels that trigger preservation, rehabilitation, and reconstruction maintenance options to determine the RSL until each trigger level is reached. The specified threshold limits that trigger preservation, rehabilitation, and reconstruction for each distress, pavement type, and road classification are shown in table 7 through table 9, respectively.

Table 7. Preservation threshold limits for construction events used in PHT analysis tool.

Surface Type	Class	IRI (inches/mi)	Cracking Percent	Cracking Length (ft/mi)	Rutting (inch)	Faulting (inch)
AC	Interstate	95	5	250	0.25	
	Primary	100	5	1,000	0.25	
	Secondary	125	5	1,000	0.35	
Rigid	Interstate	95	5			0.05
	Primary	100	5			0.05
	Secondary	125	5			0.10

Blank cell = Measurement not appropriate for pavement type (e.g., no measurements taken).

Table 8. Rehabilitation threshold limits for construction events used in PHT analysis tool.

Surface Type	Class	IRI (inches/mi)	Cracking Percent	Cracking Length (ft/mi)	Rutting (inch)	Faulting (inch)
AC	Interstate	125	10	1,000	0.35	
	Primary	150	15	2,000	0.50	
	Secondary	150	20	2,000	0.50	
Rigid	Interstate	150	10			0.10
	Primary	150	10			0.10
	Secondary	150	10			0.15

Blank cell = Measurement not appropriate for pavement type (e.g., no measurements taken).

Table 9. Reconstruction threshold limits for construction events used in PHT analysis tool.

Surface Type	Class	IRI (inches/mi)	Cracking Percent	Cracking Length (ft/mi)	Rutting (inch)	Faulting (inch)
AC	Interstate	170	20	2,000	0.40	
	Primary	220	30	2,000	0.60	
	Secondary	220	30	2,500	0.80	
Rigid	Interstate	170	15			0.15
	Primary	220	15			0.20
	Secondary	220	20			0.20

Blank cell = Measurement not appropriate for pavement type (e.g., no measurements taken).

The following rules were used when considering the feasibility of construction events:

- No more than two successive preservation treatments should be suggested.
- Do not allow multiple rehabilitations within a 10-year period.
- Do not allow multiple reconstructions within a 20-year period.

Table 10 provides the benefit for the various metrics based on construction event and as a function of percent decrease from the existing condition. For example, R&R remove all distress and reduce IRI to a minimum of 50 inches/mi, and preservation treatments reduce cracking length by 90 percent. Once a treatment is selected by the RSI module based on the existing conditions, the distress and IRI values are reset by applying the below percentages to the existing values and are considered the new condition after construction.

Table 10. PHT analysis tool treatment benefit by percent decrease in existing value.

Construction Event	Percent Cracking	Cracking Length	Rutting	IRI
Do nothing	0	0	0	0
Preservation	100	90	50	20
Rehabilitation	100	100	100	100 (not less than 50 inches/mi)
Reconstruction	100	100	100	100 (not less than 50 inches/mi)

An overview of the relationship of the RSI module within the PHT analysis tool is provided in figure 7. It shows that the RSI analysis was executed using the selected highway sections obtained from the PHT analysis tool database. Once the RSI analysis was complete, the LLCCs for each highway section and the overall system were determined. The execution of the RSI analysis was done using the RSI subroutine explained in figure 3, as denoted by the double box symbol in figure 7.

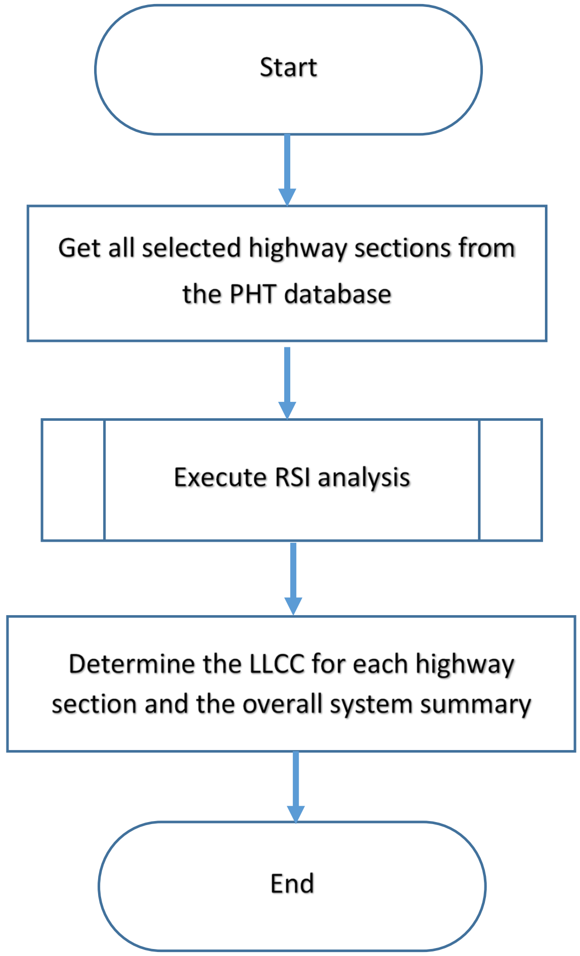


Figure 7. Flowchart. PHT analysis tool RSI module overview.

The flowchart in figure 3 shows that the RSI algorithm used available highway sections to identify a year that triggered a construction event based on the prediction models (within PHT analysis tool). A 1-year time-step interval was used in this process. If the year identified did not reach the analysis period end and the treatment could be applied based on the rules listed previously, both a “do nothing” and an “apply treatment” scenario were created. When the rules listed did not allow the treatment to be applied, a “do nothing” scenario was created, the inputs were updated to change to the next level’s threshold value (i.e., from preservation to rehabilitation or rehabilitation to reconstruction), and the link was looped through the prediction models again until the analysis period was reached. This loop was performed to account for all construction thresholds (preservation, rehabilitation, and reconstruction). Once the end of the analysis period was reached, the LLCC option from all possible scenarios was selected and output to the summary table. Figure 8 provides more details of performing the prediction models, incrementing the input values, and updating the threshold values described as a part of the RSI algorithm in figure 3.

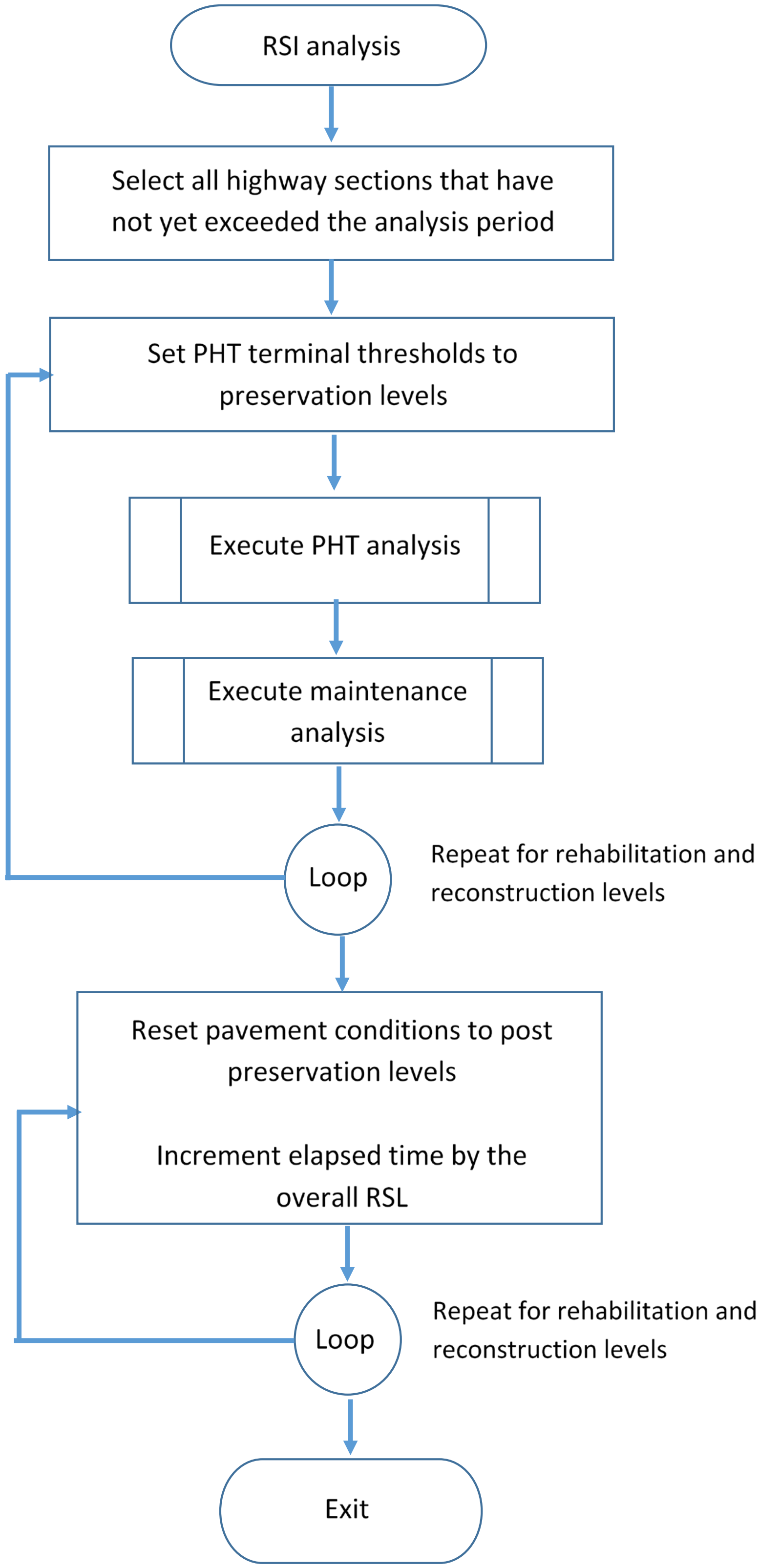


Figure 8. Flowchart. PHT analysis tool RSI algorithm.

Validation Using RSI Module

This section provides an overview of the validation effort using the RSI module developed for the PHT analysis tool. It was expected that the validation would use a representative sample of HPMS 2010+ data for national-level validation. However, the validation effort never reached that point, as is documented later in this section. The validation effort described during the remainder of this section represents the efforts undertaken during the RSI module testing and acceptance phase. The data used during this effort was a subset of HPMS 2010+ data from Idaho. This sample data was used as it passed the PHT analysis tool data validation stage. Within the PHT analysis tool, there are several validation rules that the data must pass such as various range and reasonableness checks. This sample also represented a range of various conditions and age of pavement as summarized in table 11. There were 100 sample sections, all of which were AC.

Table 11. Sample HPMS 2010 + Idaho data summary.

	Minimum	Maximum	Average
AADT	4,000	22,000	8,942
IRI (inches/mi)	91	190	126.5
Rutting (inch)	0.1	0.3	0.21
Transverse cracking length (ft/mi)	100	1,440	562.4
Fatigue cracking (percent)	0	25	9.1
Last year improved	1970	2010	2008
Last year constructed	1962	1999	1974
Thickness (inch)	8	14	8.5

Figure 9 shows the maintenance thresholds used by the RSI module. These were input based on the values in table 7 through table 9.

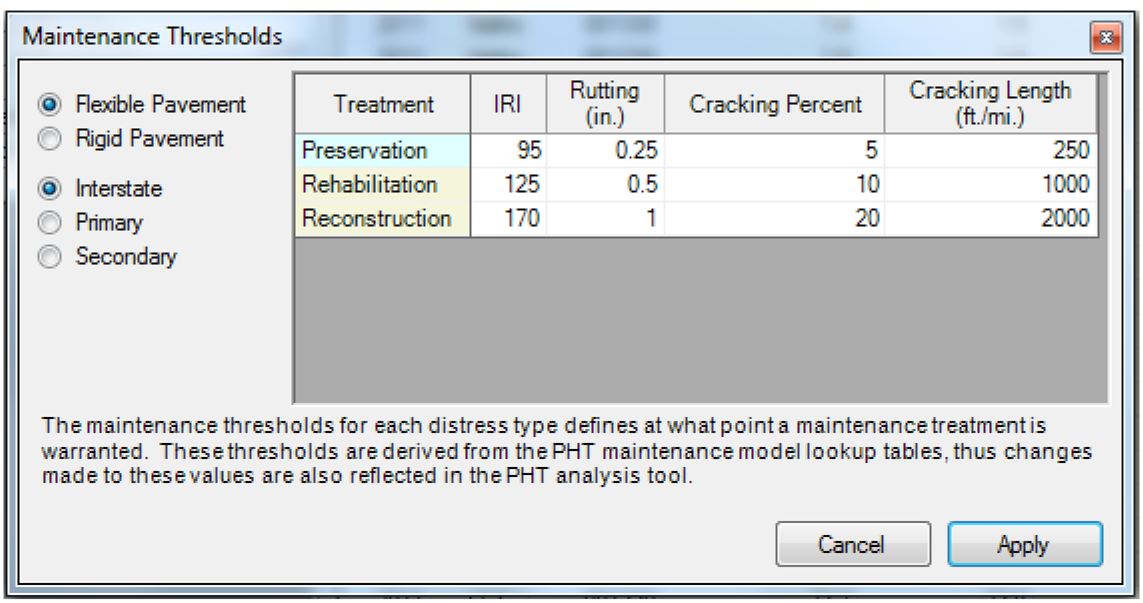


Figure 9. Screenshot. Maintenance thresholds.

The options that are available within the RSI module are depicted in figure 10 and include setting the maximum number of analysis iterations, discount rate (percent), ability to overwrite the limited pavement lives, application of minimum BCR to maintenace treatments, and the maintenace feasibility constraints. The feasiblity constraints allow the user to change the number of consectuive preservation treatments or the minimum number of years between rehabilitation or reconstruction treatments. The RSI module uses the same database input through the PHT analysis tool for analysis with these maintenance thresholds and RSI properties.

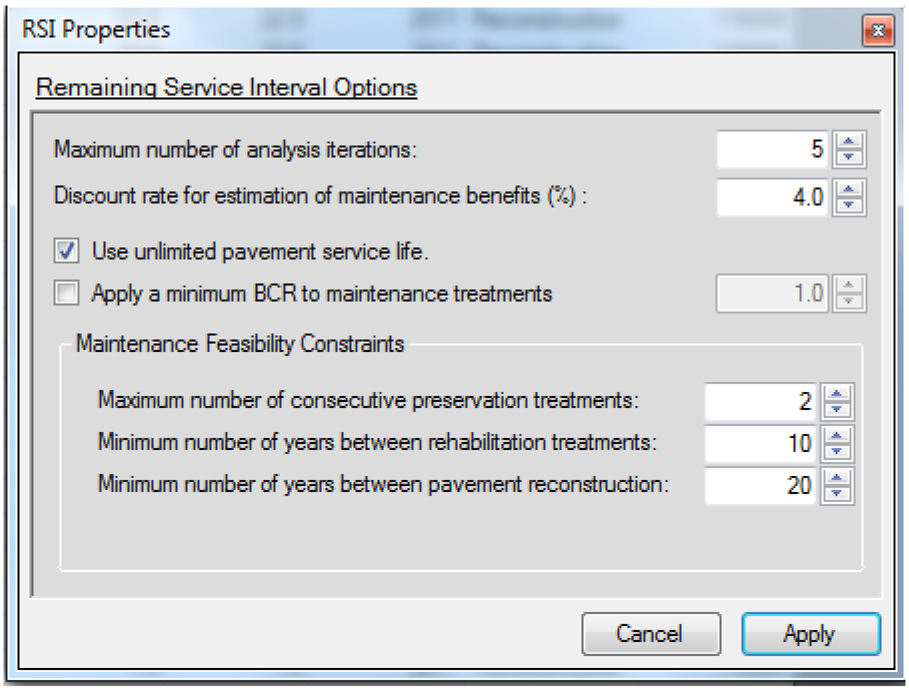


Figure 10. Screenshot. RSI properties options.

RSI Validation Results

Running the RSI module produces sections and summary reports. The RSI sections report, as depicted in figure 11, shows each pavement section based on beginning and end points and the event year, type, and cost. For example, for pavement section ID 1, reconstruction is triggered in 2011 at a cost of $116,000 for the section. The summary report, as depicted in figure 12, provides a summary of the preservation, rehabilitation, and reconstruction costs for each year a treatment is required. For the sample data used, $4,454,400 and $116,000 are needed for reconstruction in years 2011 and 2014, respectively, while $16,800 is needed for preservation in 2016. The summary table is based on accumulating the costs for each pavement section for the specified event years and construction event types.

ID	state_code	route_id	begin_point	end_point	event_year	event_type	event_cost
1	16	001330	22.2	22.3	2011	Reconstruction	116000
2	16	001330	22	22.1	2011	Reconstruction	116000
3	16	001330	21.9	22	2011	Reconstruction	116000
4	16	001330	21.7	21.8	2011	Reconstruction	116000
5	16	001330	21.6	21.7	2011	Reconstruction	116000
6	16	001330	21.8	21.9	2011	Reconstruction	116000
7	16	001330	22.1	22.2	2011	Reconstruction	116000
8	16	001330	23.4	23.5	2011	Reconstruction	116000
9	16	001330	23.047	23.1	2011	Reconstruction	61480
10	16	001330	23.2	23.3	2011	Reconstruction	116000
11	16	001330	23.1	23.2	2011	Reconstruction	116000
12	16	001330	23	23.023	2011	Reconstruction	26680
13	16	001330	22.9	23	2011	Reconstruction	116000
14	16	001330	23.023	23.047	2011	Reconstruction	27840

Figure 11. Screenshot. RSI results Idaho sections report.

event_year	preservation_cost	rehabilitation_cost	reconstruction_cost
2011	0	0	4454400
2014	0	0	116000
2016	16800	0	0

Figure 12. Screenshot. RSI results summary report.

Although the pavement sections used for analysis varied by condition, age, and structure, 96 percent of the sections triggered reconstruction in 2011, which triggered further investigation. It appeared that the pavement sections (even those that were classified as in good condition) were deteriorating beyond the reconstruction thresholds within a year's time. The RSI module contains an analysis tab that was used for debugging purposes. This analysis tab contains each highway section and shows the possible RSI paths for each section as well as the historical dates, premaintenance conditions, and postmaintenance conditions. The data in this analysis tab were used to further investigate the possible cause of the overwhelming number of reconstruction triggered in 2011.

Figure 13 depicts a sample RSI analysis tab for a pavement section. Under the "Possible RSI Paths" portion of the tab, there are two distinct possible RSI paths. Both paths begin with a reconstruction in 2011 at a cost of $116,000. After the reconstruction, there are two scenarios: (1) preservation in 2013 at a cost of $16,800, followed by either preservation in 2015 (and many other treatments as denoted by the plus mark next to the path) or reconstruction in 2022 at a cost of $116,000, or (2) reconstruction in 2088 at a cost of $116,000. This is not logical, since in the first scenario, a preservation treatment is selected in 2013 followed by a reconstruction in 2022, while in the second scenario, no treatment is selected until 2088, when a reconstruction is warranted while still maintaining acceptable LOS. This shows a shortcoming of the models within the PHT analysis tool that is summarized under PHT Analysis Model Issues.

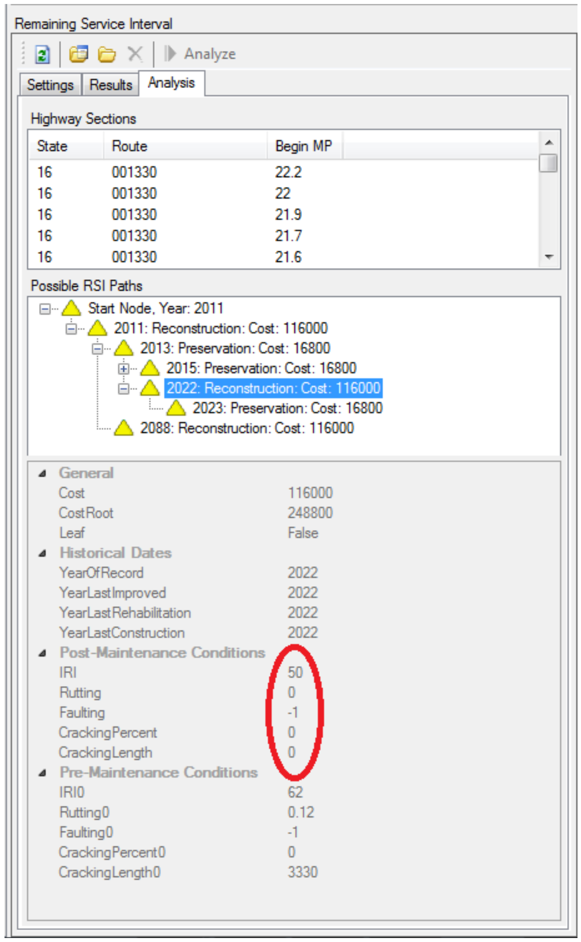


Figure 13. Screenshot. RSI module analysis tab, 2022 reconstruction.

Figure 14 is similar to figure 13 with the difference being the RSI path that is highlighted. Figure 13 shows the 2022 reconstruction, while figure 14 shows the 2023 preservation that follows the reconstruction in 2022. The importance of these figures is provided by the premaintenance and postmaintenance conditions for each treatment. As shown in figure 13, the postmaintenance conditions after the reconstruction in 2022 are an IRI of 50 inches/mi, rutting of 0 inch, cracking of 0 percent, and cracking length of 0 ft/mi. These values represent expected values after a reconstruction.

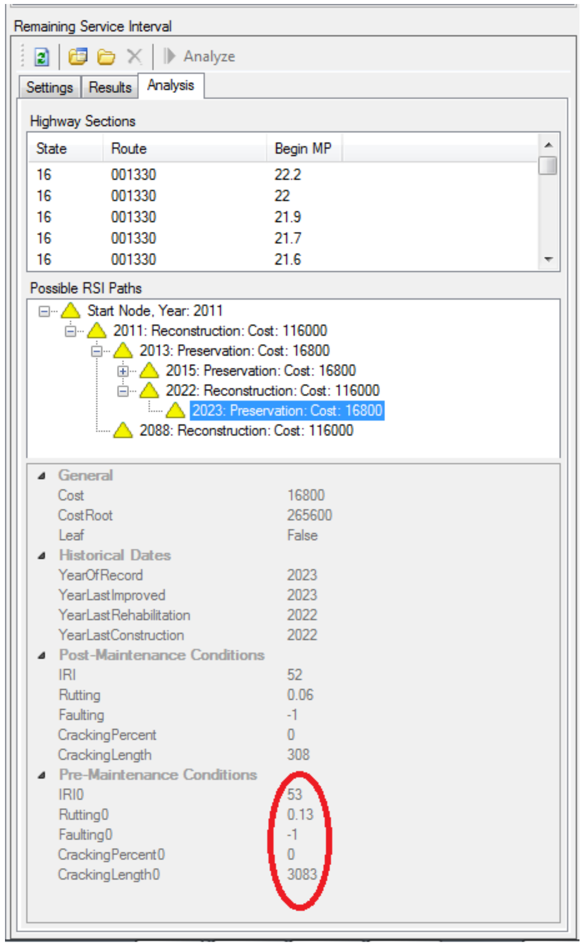


Figure 14. Screenshot. RSI module analysis tab, 2023 preservation.

The premaintenance conditions represent the conditions at the time that the treatment, in this case preservation, was suggested. For this example, the pretreatment conditions in figure 14 represent the condition in 2023 prior to placing the preservation treatment, which is an IRI of 53 inches/mi, rutting of 0.13 inch, cracking of 0 percent, and cracking length of 3,083 ft/mi. Based on there being a reconstruction in 2022 and the cracking length value being reset to 0 ft/mi, such an exponential increase in cracking length 1 year later was not expected. This cracking length also exceeds the threshold for preservation (and reconstruction), which makes this RSI path a non-viable option. This is denoted by the RSI leaf in figure 13 being false. Within the RSI module, a node (e.g., 2022 reconstruction highlighted in figure 13) is categorized as true if its year is at the end of the analysis period and any of its children (e.g., future year treatments) is beyond the analysis period.

In this example, because the premaintenance values as depicted in figure 14 would trigger a reconstruction, and a reconstruction was placed in the previous year, this violates the rule of no reconstructions within a 20-year period of a reconstruction. Therefore, this RSI path is not valid, and the leaf was classified as false. Although the RSI path was not valid, this RSI path was beneficial because it showed a possible issue with the PHT analysis tool performance models used to predict the distress values. Since this is not a valid RSI path, it does not appear in either the RSI results sections or summary reports.

Discussion of Validation Results

As a result of the unexpected results from the previous example, further investigation into the PHT analysis tool performance models, PHT analysis tool and RSI module input data (HPMS 2010+), and RSI computation module was pursued.

PHT Analysis Tool Model Issues

The PHT analysis tool uses simplified MEPDG-based pavement performance prediction models.[24] Although investigation into the appropriateness of these models is outside the scope of this RSI project, consideration into the model predictions was given during the testing and validation phase of the RSI module as a result of the seemingly inaccurate results the RSI module was producing. The investigation needed to determine whether the inaccuracies were due to the pavement prediction models used by the PHT analysis tool, the implementation of the RSI algorithm within the RSI module developed for the PHT analysis tool, the HPMS data inputs used by both the PHT analysis tool and the RSI module, or a combination of two or more of these factors.

As part of the investigation, the number of transverse cracks generated by PHT analysis tool was looked at in more detail because the projected value of 3,000 cracks/mi 1 year after reconstruction (see figure 14) seemed inaccurate. The forecasting models from the PHT analysis tool were obtained from the PHT analysis tool documentation.[4] Figure 15 provides the transverse cracking equation used by the PHT analysis tool, figure 16 provides the equation for the factor used in figure 15, and figure 17 provides the PHT analysis tool HMA binder viscosity equation. The air voids, percent passing, and mean annual air freeze-thaw cycles are statewide default values contained in the PHT analysis tool. Data for one section (from the dataset used for the validation) was used to test the equation. The default values shown in table 12 were used because they correspond to the Idaho values used earlier. The *A* and *VTS* values are the regression intercept and regression slope of viscosity temperature susceptibility for an HMA binder with performance grade 58-22. Using these default values, the projected number of transverse cracks per mi is 1.31, which seems reasonable for a pavement 1 year after reconstruction, but it does not compare well with the 3,000 cracks/mi projected by PHT analysis tool. It was found, however, that the PHT analysis tool reported value can be replicated if the temperature in the viscosity equation is reported in Fahrenheit instead of Rankine, as required. This is one example of the issues identified with the models used within the PHT analysis tool.

$$T_{CRK} = \left(\frac{AGE}{AGE+1}\right)\frac{6000}{1+1.03^{(-5.9033AGE+FACTOR)}}$$

Figure 15. Equation. PHT analysis tool transverse cracking equation.

$$FACTOR = 1472.2 + 3.167 * H_{HMA} - 879.8 loglog\eta - 16.98 * V_a - 3.385 * PCT_{3/4} - 0.25 * FTCYC$$

Figure 16. Equation. Factor equation.

Where:

T_{CRK} = Number of transverse cracks per mi.

H_{HMA} = HMA thickness, inches.
η = Aged viscosity at HMA surface, cP.
V_a = HMA mix as-constructed air voids, percent.
$PCT_{3/4}$ = Percent passing $^3/_4$-inch sieve for the HMA mix.
$FTCYC$ = Mean annual air freeze-thaw cycles.

$$loglog\eta_{orig} = A + VTSlogT_R$$

Figure 17. PHT analysis tool HMA binder viscosity equation.

Where:

η_{orig} = Unaged HMA binder viscosity (at reference temperature 77 °F), cP.
T_R = Temperature, Rankine (reference temperature is 77 °F, convert to Rankine).

Table 12. Input data for PHT analysis tool models.

Variable	Value
Age	1 year
H_{HMA}	9 inches
V_a	3.19 percent
FTCYC	127.4
A	11.787
VTS	-3.981

Concurrent with the investigation, members of the project team were also working on other FHWA-sponsored projects related to the performance models contained in the PHT analysis tool through both the HERS and the National Pavement Cost Model (NAPCOM). Through these projects, as well as with issues experienced during the FHWA-sponsored "Improving FHWA's Ability to Asses Infrastructure Health" project with the PHT analysis tool, the project team concluded that there was enough evidence to suggest that there are issues with the simplified MEPDG models that are contained in various forms in the PHT analysis tool, HERS, and NAPCOM. (See references 4, 26, and 30.)

HPMS 2010+ Data Issues

There have been many studies that have investigated the quality, completeness, or issues of the HPMS 2010+ dataset. (See references 30 through 33.) A chapter in the *Interstate Pavement Condition Sampling Phase I Report* provides a literature review of these references.[(34)] Some of the highlights from the literature review that are relevant to the issues and challenges faced within this project include HPMS data consistency, completeness, data requirements, and algorithms for collection and use with national performance measures.

However, what these studies did not investigate fully, or at all in some instances, was the appropriateness of HPMS data across a section. These data need to be further investigated to determine whether elements such as total pavement structure, traffic demand, pavement condition (as a function of reported IRI, distress and rutting, or faulting), and climate are appropriate when used as inputs to models such as the PHT analysis tool. For example, an interstate pavement section with asphalt thickness of 3.5 inches placed 10 years ago and with an AADT of 50,000 vehicles that is showing no distress or rutting and acceptable IRI may be suspect because the asphalt thickness appears inadequate for the traffic level and time in service. As such, this section needs to be investigated to see if this thickness value is appropriate or not. This investigation could lead to findings such as the section expecting to see an exponential increase in cracking length after a reconstruction based on the factors considered or that it is unlikely that these reported values are actually reflective of the true pavement section.

Although further investigation of this issue is beyond the scope of the RSI project in question, the challenges and issues faced during this project resulted in recommendations regarding further investigation into the quality, completeness, and appropriateness of use of HPMS data in performance models for future research and that are presented in chapter 6.

RSI Computation Module

Notwithstanding the issues with the performance models and HPMS 2010+ data inputs, the project team needed to test the performance of the RSI module to check whether the computations within the module were accurately following the RSI algorithm. Although the results from the RSI module were not reliable as a result of the issues with the performance models as implemented within PHT analysis tool and input data, the functionality of the RSI module was tested for acceptance so that in the future, when the issues with the performance models and data inputs have been addressed, the RSI module will be available for use.

The testing of the RSI module included checking the accuracy of the condition values that triggered treatment against threshold values, resetting maintenance levels once a treatment was applied, and not including RSI paths that violated the rules set forth in the algorithm.

Additional datasets were created for a limited number of sections that included data that would be considered complete, consistent, and usable as inputs for performance models. Although these datasets addressed the issue with the input data, they still faced the issue with the performance models. Therefore, although these results may seem to have improved over previous results, they were still not reliable. However, these datasets did provide more insight into the performance of the RSI module.

Through these activities, the project team concluded that the RSI module was performing as expected and following the RSI algorithm accurately.

Summary of Findings and Conclusions

Based on the discussion of the issues associated with the PHT analysis tool performance models and use of HPMS 2010+ data as input to the PHT analysis tool and RSI modules, it was concluded that the PHT analysis tool in its current form cannot be used for the validation of the RSI concept. As a result, the RSI validation at the strategic level using HPMS 2010+ data could not be completed.

SUMMARY

This chapter presented an overview of the application and validation of the RSI framework at the project, network, and strategic levels. Some of the issues and challenges faced with validating the RSI concept include the following:

- Application using WSDOT as follows:
    - Limited range of treatment options considered and their application mostly within narrow range of pavement condition.
- Application using HPMS 2010+ as follows:
    - Data consistency and completeness for strategic level inputs.
    - Suspect PHT analysis predictions that use simplified MEPDG models.[29]

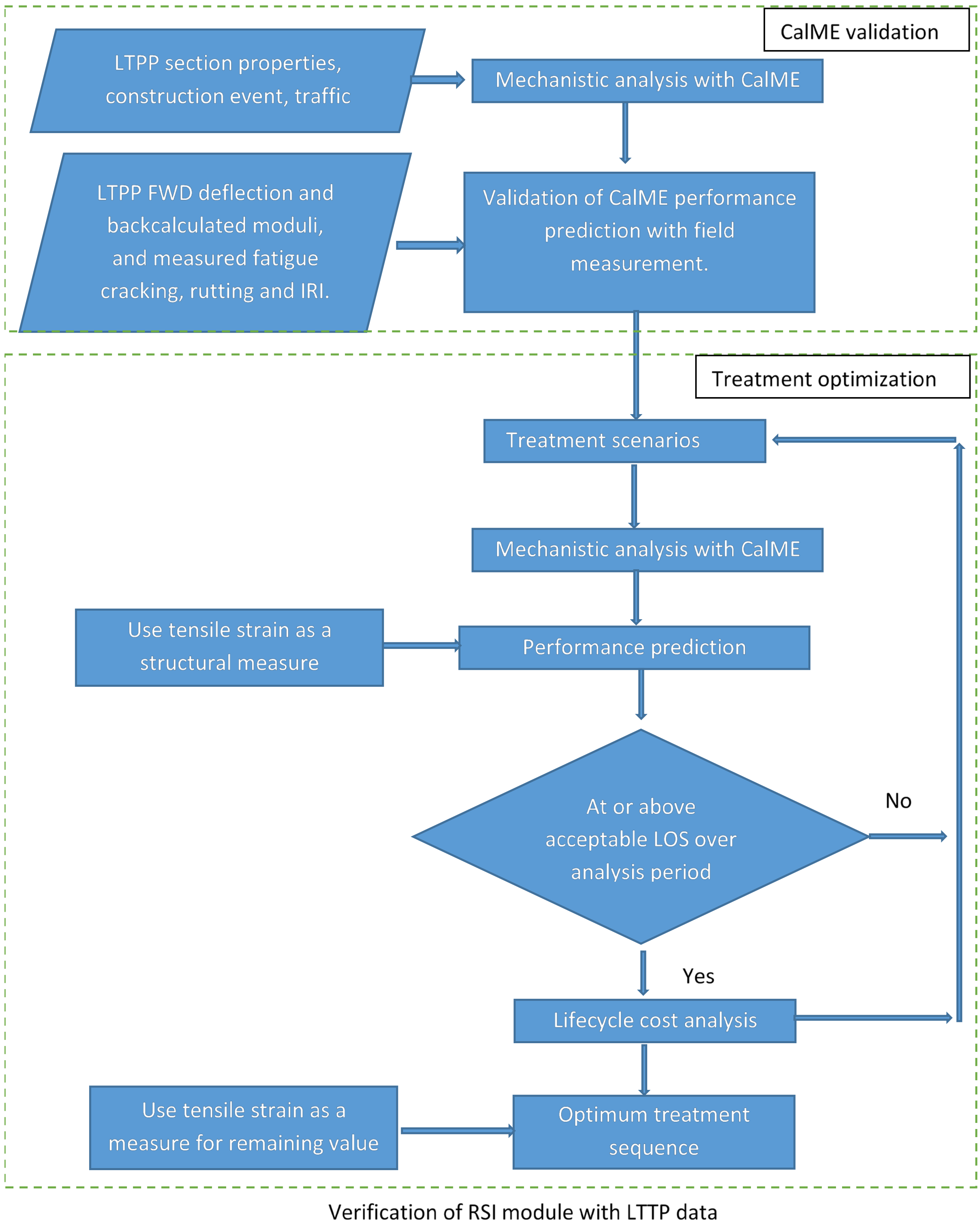
Chapter 4 provides details on the project-level validation using LTPP data and CalME.

CHAPTER 4. APPLICATION AND VALIDATION OF RSI FRAMEWORK AT THE PROJECT LEVEL

INTRODUCTION

Data collected as part of the LTPP Program provided an excellent opportunity to apply the comprehensive LCCA-based RSI methodology in a project-level demonstration and subsequent reporting of project treatment needs within the context of the RSI concept and terminology. In practice, network-level LCCA is possible if each section in the network has detailed data, typically called project-level data; the analysis shown in this chapter can be extended to each project section in the network. In this example, LTPP data is being used as representative project-level data.

Thyagarajan et al. presented a methodology for incorporating structural measurements to track flexible pavement structural condition over time and assessing future rehabilitation needs at a network level to address structural adequacy in addition to surface condition at LLCC.(35) The article showed that mechanistic-empirical pavement analysis tools such as CalME can be used to determine structural performance extension from a selected treatment applied at a given condition.(5) The estimated benefit (performance extension) combined with treatment cost are used in the LCC analysis to identify the optimum treatment sequence. Mechanistic-empirical analysis also enables the quantification of the monetary loss of delaying the optimum treatment. This chapter describes the application of the methodology proposed by Thyagarajan et al. using data from LTPP test section 06-0505 in which both structural and function conditions have been monitored at regular interval as part of LTPP monitoring efforts.(35) Figure 18 depicts the flowchart for this methodology. Finally, the identified optimum treatments are reported using the RSI terminology.



FWD = Falling weight deflectometer.

Figure 18. Flowchart. Project-level validation.

LTPP TEST SECTION

The LTPP database includes periodical measurements on distress performance, structural evaluation, and traffic for each monitored section. In addition, the data collection effort includes section inventory, material testing (laboratory and field), climate, and M&R data. LTPP InfoPave™ offers a gateway to LTPP data as well as to findings from data analyses and extensive documentation for the many aspects of LTPP experiment design, data acquisition, quality control, and data dissemination. LTPP test section 06-0505 in California, which was part of LTPP's *Specific Pavement Studies on Rehabilitation of Asphalt Concrete Pavements* (SPS-5 experiment) was used in this project.[36] The layer types and construction events for the selected section are summarized in table 13. The pavement section was constructed in June 1966, and the M&R history for the section was available from January 1987 when the section was included in the LTPP Program. The first recorded treatment event was a mill and overlay applied in February 1992. The section was taken out of study from the LTPP Program in June 2007.

Table 13. Construction events and layer information for LTPP test section 06-0505.

Layer Information			Construction Events			
			CN 1: Initial Structure January 1987	CN 2: Mill and Overlay February 1992	CN 3: Crack Sealing March 2000	CN 4: Resurfacing July 2000
Layer Number	Layer Type	Layer Material Description	Thickness (inch)	Thickness (inch)	Thickness (inch)	Thickness (inch)
1	Subgrade (untreated)	Coarse-grained soils: poorly graded sand with silt				
2	Unbound (granular) subbase	Soil-aggregate mixture (predominantly coarse-grained)	20	20	20	20
3	Bound (treated) base	Cement aggregate mixture	5.2	5.2	5.2	5.2
4	AC layer	Hot mixed, hot laid AC, dense graded	4.7	3	3	3
5	AC layer	Hot mixed, hot laid AC, open graded	0.5	0	0	0
6	AC layer	Hot mixed, hot laid AC, dense graded		3.1	3.1	3.1
7	AC layer	Plant mix (emulsified asphalt) material, cold laid				0.2

CN = Construction number.
Blank cell = Layer 1 (subgrade) thickness is not measured (assumed to be semi-infinite) and/or layers 6 and/or 7 do not exist.

Figure 19 shows the measured traffic loading for LTPP test section 06-0505. As shown in this figure, an annual traffic growth of 1 percent was computed by fitting a linear trend to the data. Figure 20 shows the measured pavement roughness (IRI), and figure 21 shows AC fatigue cracking and AC rutting for this test section over time. As shown in these figures, the construction events detailed in table 13 reduced the measured amount of roughness, rutting, and cracking.

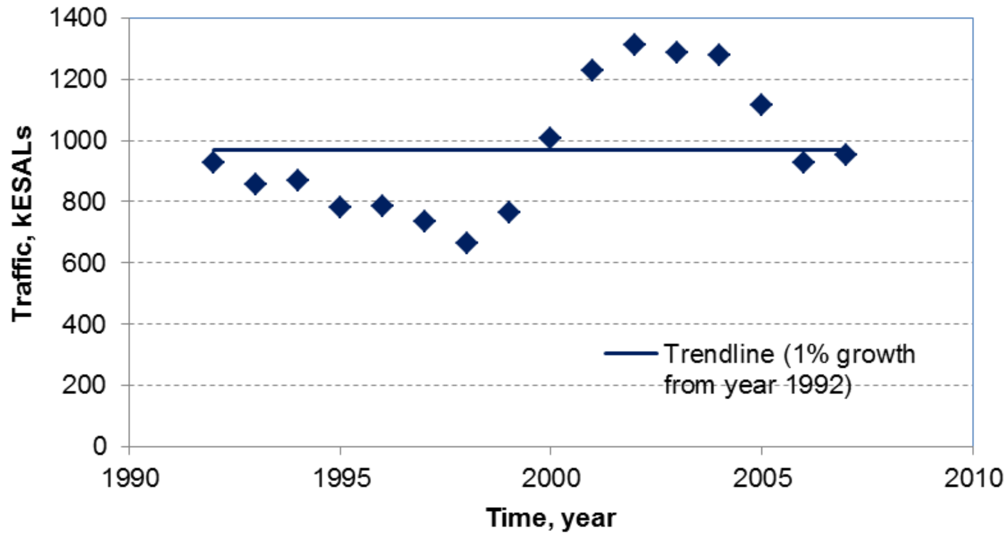


Figure 19. Graph. Annual traffic on LTPP test section 06-0505.

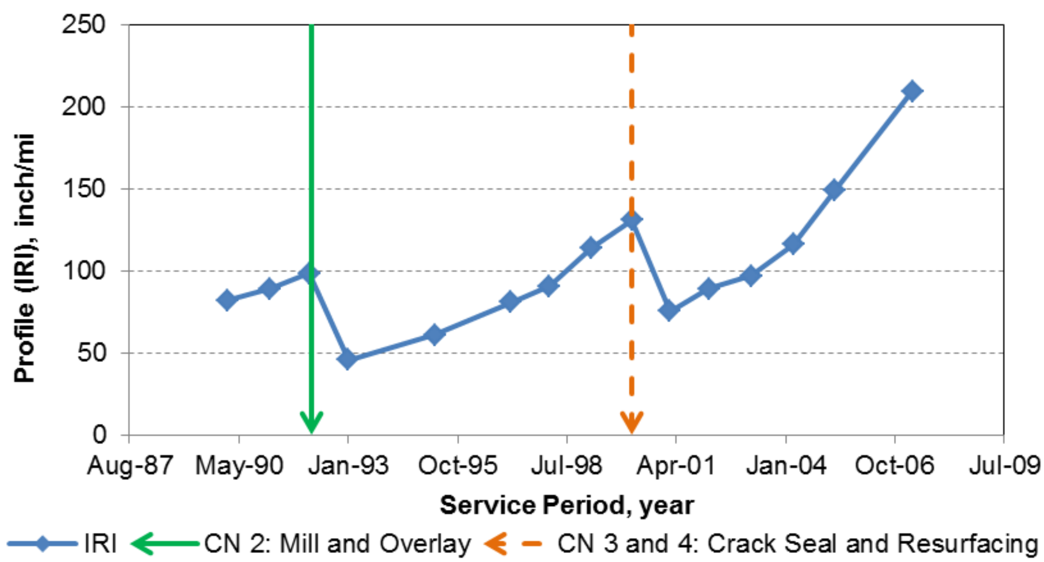


Figure 20. Graph. Measured profile on LTPP test section 06-0505.

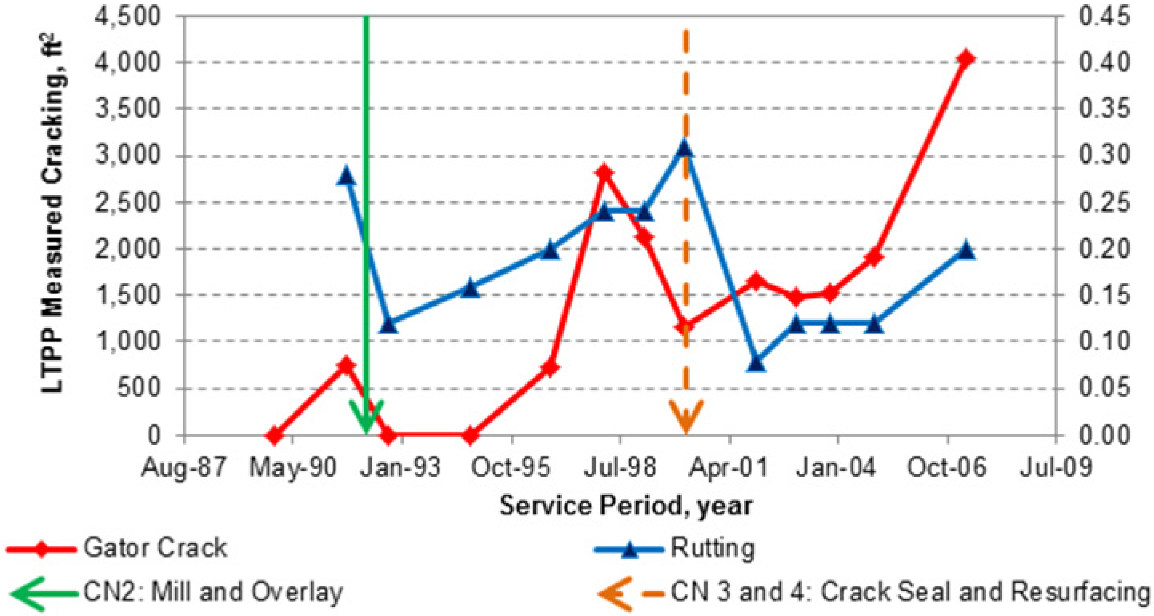


Figure 21. Graph. Measured fatigue cracking and AC rutting on LTPP test section 06-0505.

Figure 22 shows the resilient modulus value at different temperatures and monitoring periods for the AC mixes used in layers 4 and 6 (see table 13). As shown in this figure, at 77 °F, the resilient modulus of both AC mixes is about 1,300 ksi. The resilient modulus test was also performed on the subbase material in April 2003. Figure 23 shows the effect of confining pressure on resilient modulus for the granular subbase layer. The resilient modulus of subbase material at a confining pressure of 5 ksi is approximately 12 ksi.

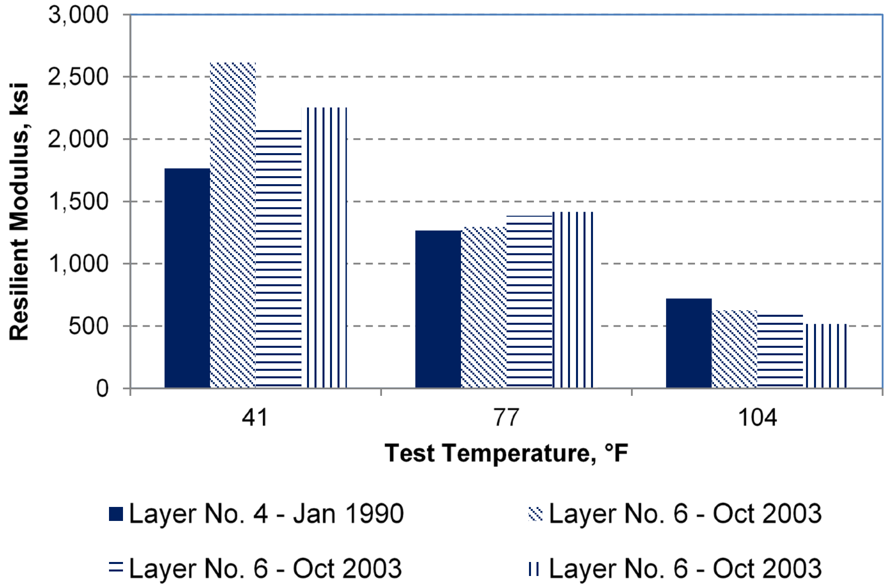


Figure 22. Graph. Resilient modulus of AC mix at different service periods for LTPP test section 06-0505.

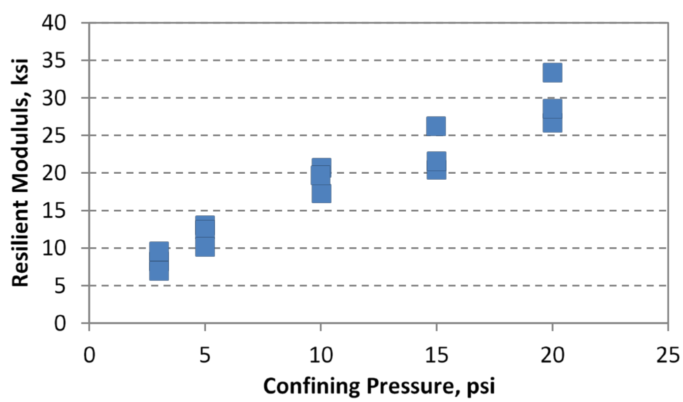


Figure 23. Graph. Resilient modulus of subbase material at different confining pressures for LTPP test section 06-0505.

Periodic FWD testing was conducted on LTPP test section 06-0505 starting in January 1990 prior to construction event 2 (mill and overlay; see table 13). LTTP InfoPave™ also contained FWD-derived backcalculated layer moduli values for the section in question computed using the EVERCALC backcalculation program. Figure 24 presents the backcalculated modulus for each structural layer of LTPP test section 06-0505. The surface temperatures measured during FWD testing are available for after February 1992. The temperature correction procedure incorporated in the EVERCALC program was used to compute AC layer modulus at a reference temperature of 77 °F, and the resulting temperature-corrected AC layer moduli are also shown in figure 24 along with the trend line. For comparison purposes, the lab-measured AC resilient moduli from figure 22 are also shown in figure 24.

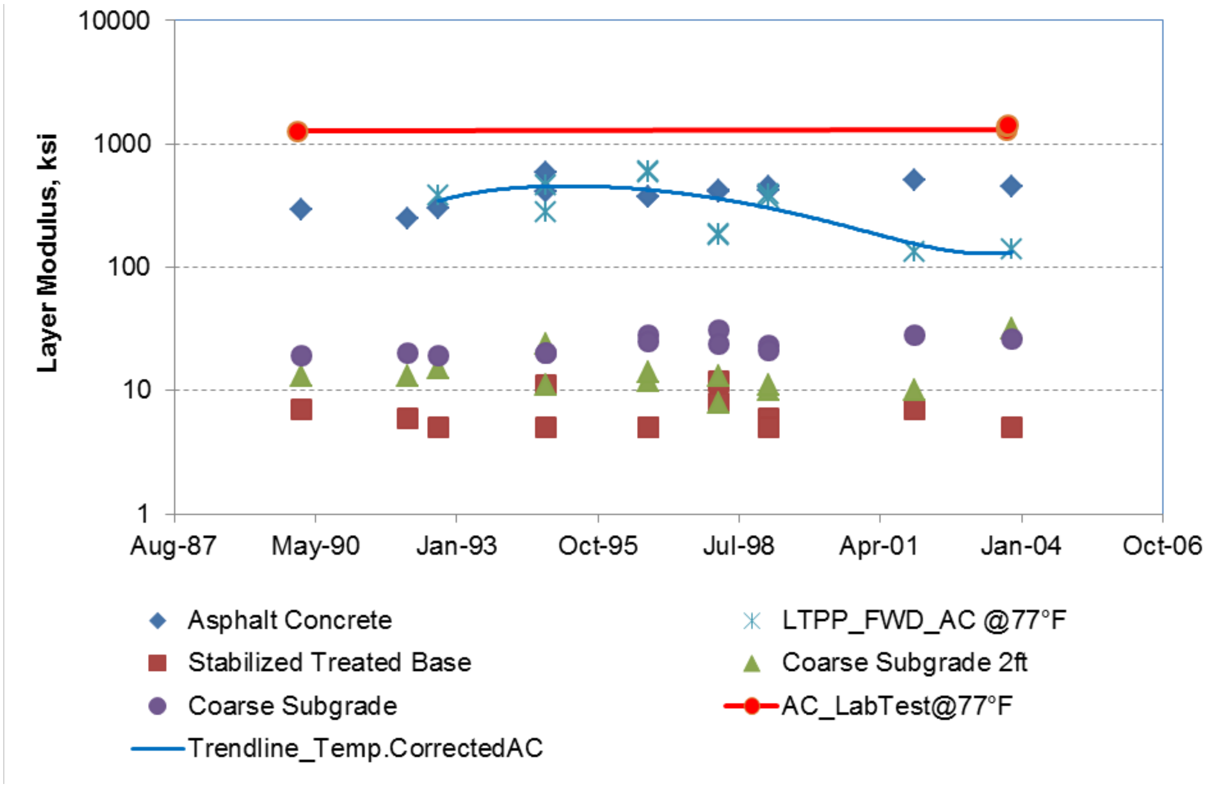


Figure 24. Graph. LTPP backcalculated layer moduli for LTPP test section 06-0505.

CalME ANALYSIS

The CalME analysis software was used in this project to predict past and future performance and then to compare the predicted performance with the measured LTPP performance. The CalME software takes into account the progressive deterioration of the pavement structure over the design period and can also consider sequence of treatments during the analysis period to preserve and provide acceptable or above acceptable LOS over the analysis period. It is important to note that the CalME transfer functions were calibrated for California conditions and are therefore applicable to the LTPP test section 06-0505.

Barstow Daggett County Airport in California is the closest first-order weather station for LTPP test section 06-0505; it is about 12 mi west of the section. Figure 25 shows the hourly air temperature profile for the section over a 3-year period. The monthly average temperature shown in the figure is the temperature used in the CalME analysis.

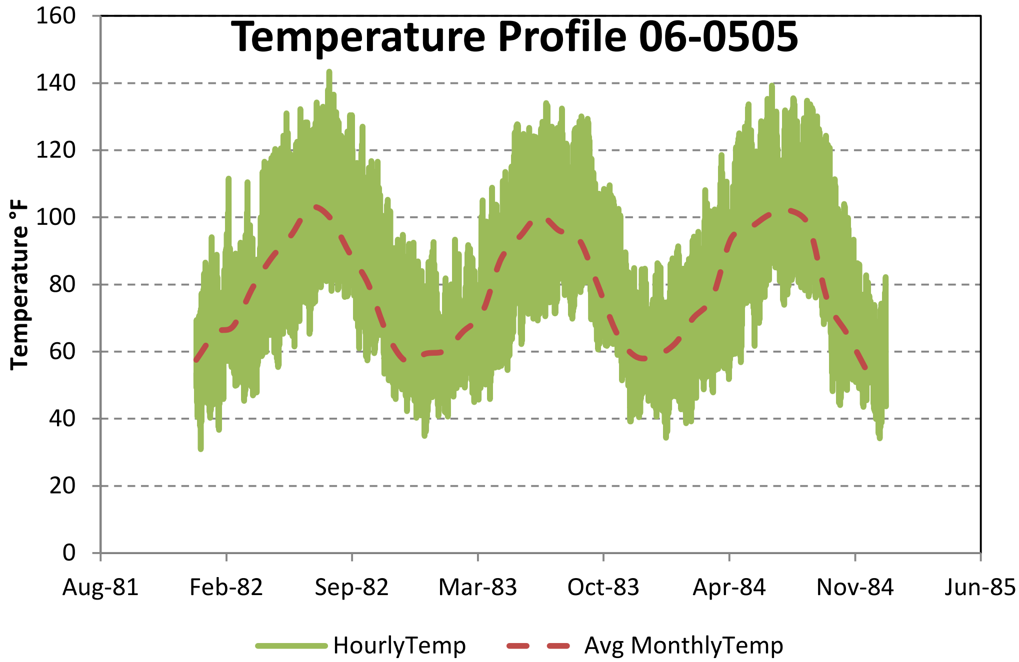


Figure 25. Graph. Three-year air temperature profile near LTPP test section 06-0505.

Figure 26 shows the layer moduli computed by CalME using the pavement section, layer properties, traffic, and climate data for LTPP test section 06-0505. The section was already in service when included in the LTPP Program; therefore, the AC properties at the time of initial construction were not available. Accordingly, default AC layer properties were assumed for layer 4 defined in table 13. Figure 26 shows the effect of seasonal fluctuation and structural deterioration on the computed layer moduli. The AC layer moduli for layers 4 and 6 show a gradual decrease over the analysis period. For comparison purposes, the AC resilient moduli from the laboratory and the FWD backcalculation (temperature corrected) and the subbase resilient moduli from the laboratory are also included in the figure. Note that all AC layers are treated as a single layer for backcalculation; therefore, the FWD-derived AC moduli are an estimate of the combined AC layers at the time of FWD testing. As shown in figure 26, significant differences exist between the laboratory-derived AC moduli and those derived from FWD backcalculation. Both sets of data were obtained directly from the LTPP database.

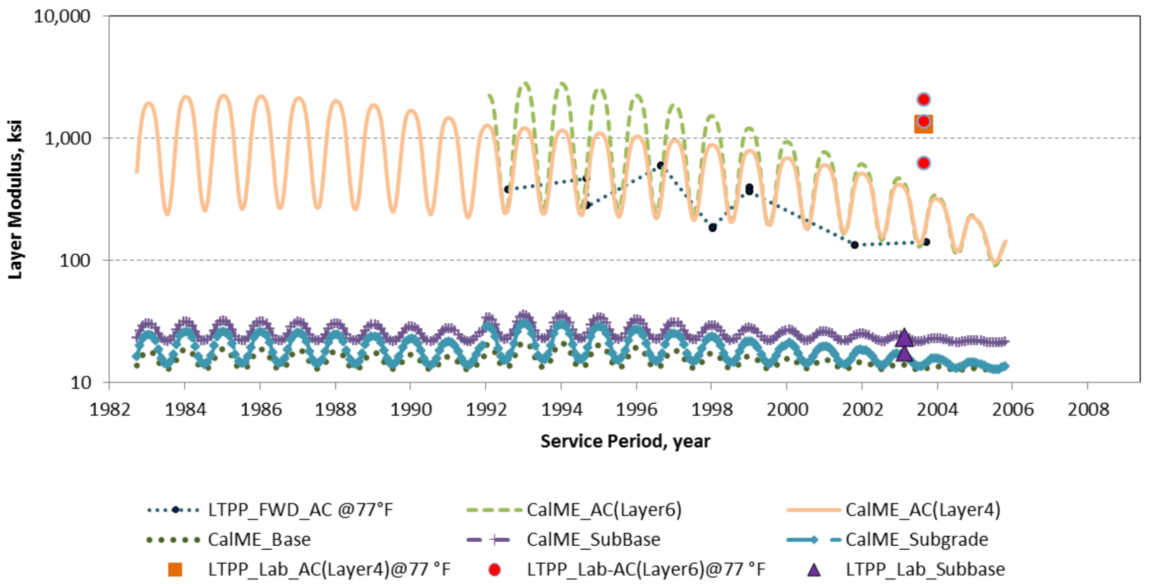


Figure 26. Graph. CalME-computed layer moduli for test section 06-0505.

Figure 27 and figure 28 compare the CalME estimated and LTPP measured fatigue cracking and rutting, respectively. These two figures clearly show that the CalME program can replicate actual field performance and therefore can be used with confidence in scheduling future treatment activities.

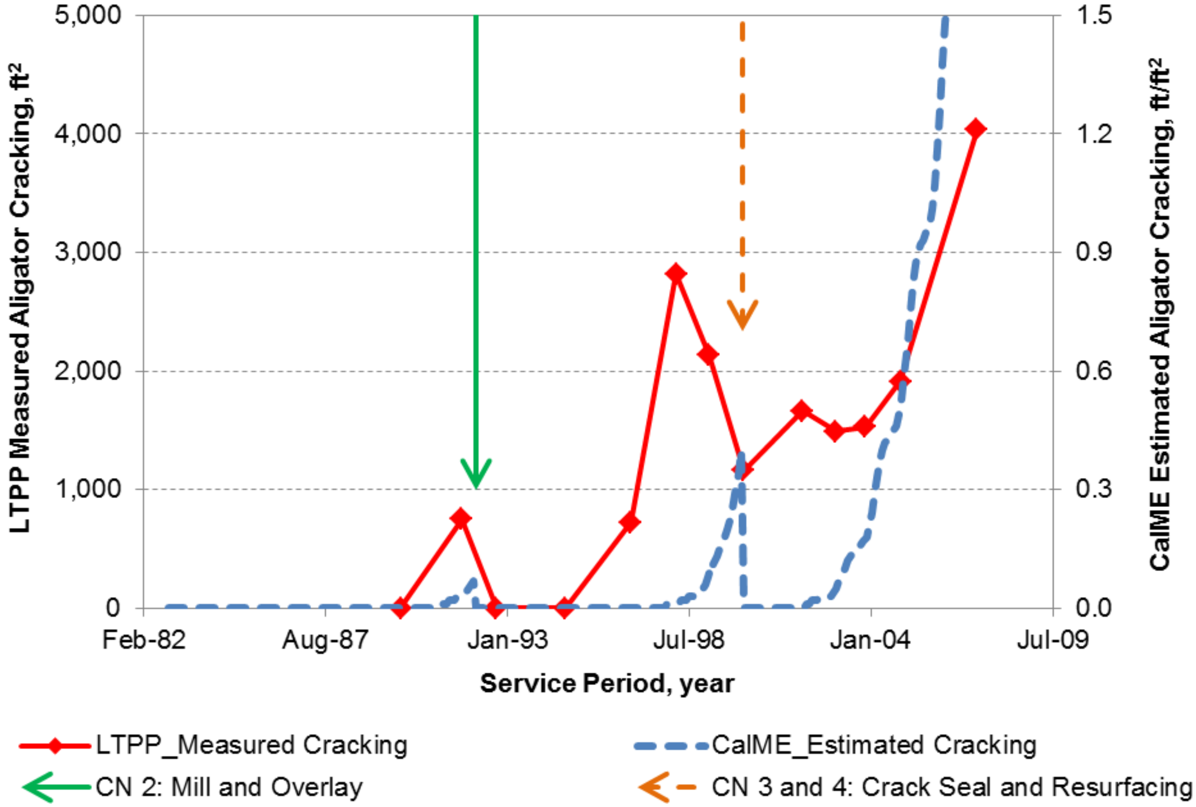


Figure 27. Graph. LTPP-measured versus CalME-estimated fatigue cracking for LTPP test section 06-0505.

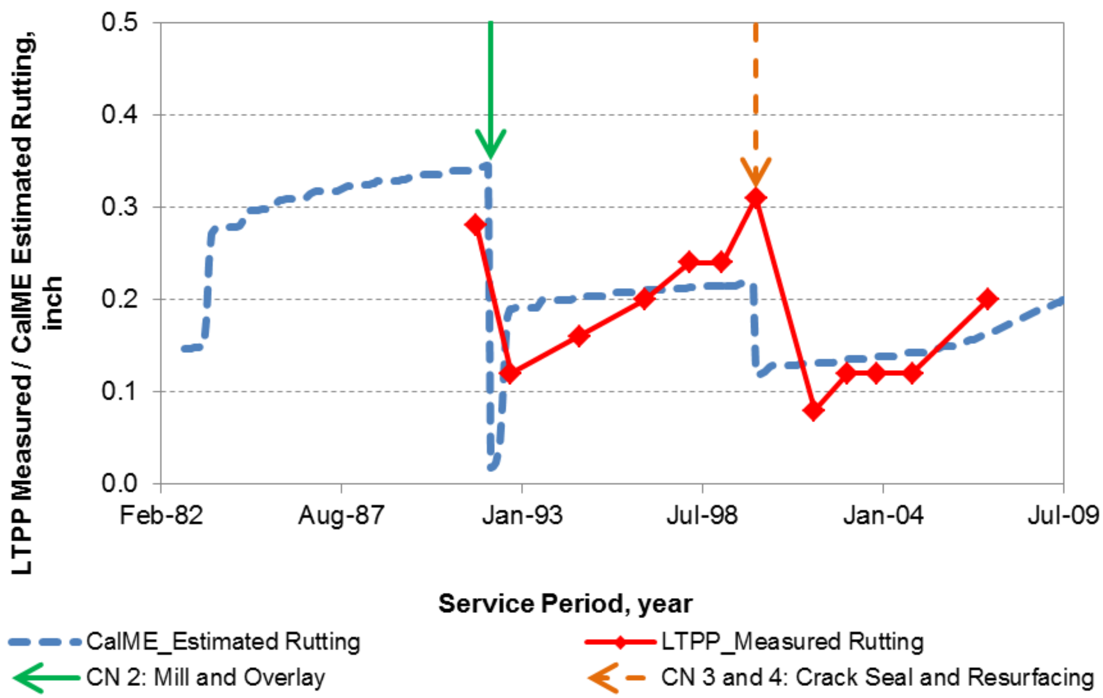


Figure 28. Graph. LTPP-measured versus CalME-estimated rutting for test section 06-0505.

INTEGRATED MECHANISTIC AND LCC ANALYSES

In this section, the optimum treatments were scheduled for LTPP test section 06-0505 based on pavement conditions in 1997. The methodology proposed in Thyagarajan et.al was used to couple both mechanistic and LCC analyses and to identify the optimum sequence of treatment types and timings that minimizes the LCC.(35)

In 1997, the last treatment applied to LTPP test section 06-0505 was mill and overlay (CN 2; see table 13) as part of the LTPP SPS-5 experiment (AC overlays on existing AC pavements).(36) A resurfacing was applied in 2000 when significant cracking was observed on the surface. Preservation treatments such as resurfacing often retard the pavement deterioration and therefore are effective when the pavement structural condition is still good. Preservation treatment applied to structurally weak pavement only temporarily conceals the structural deterioration that occurs under the surface, thereby limiting future treatments to only costlier treatments such as thick overlays. The availability of continuous pavement structural data coupled with integrated mechanistic and LCC analysis would identify the appropriateness of the selected treatment type (preservation versus rehabilitation) in serving the objective of maintaining the pavement at or above an acceptable LOS while minimizing LCC over its service period.

Five different treatment scenarios were evaluated with the CalME program using the LTPP test section 06-0505 pavement condition data for 1997. In all scenarios, the minimum LOS was established as maintaining the pavement below an IRI threshold value of 140 inches/mi. The five scenarios were as follows:

- **Scenario 1:** Resurfacing in 2000, which was the actual treatment applied to the LTPP test section that was a defined prescriptive treatment mandated by the experiment and not tailored to actual site conditions (see table 13).
- **Scenario 2:** Resurfacing in 2000 followed by mill and overlay in 2003.
- **Scenario 3:** Mill and overlay in 2000.
- **Scenario 4:** Mill and overlay in 1998.
- **Scenario 5:** Resurfacing in 2000 followed by mill and thicker overlay in 2003.

Figure 29 shows the amount of fatigue cracking estimated by CalME for these five scenarios. As expected, the fatigue performance is a function of both treatment type and its time of application. Table 14 shows the LCCA for the five treatment scenarios. The table includes the performance extension computed by CalME for each treatment scenario to reach a cracking level of 0.15 ft/ft2. The costs for the resurfacing, mill and overlay, and mill and thicker overlay treatments were assumed to be $60,000, $300,000, and $400,000, respectively. A 4-percent discount rate was used in the LCCA. In 1997, the tensile strain at the bottom of the AC layers due to the application of a 9,000-lb load with 120-psi tire pressure and 12-inch dual tire spacing was estimated to be 163 microstrain, as computed by *Jacob Uzan Layered Elastic Analysis* (JULEA) using the CalME computed modulus.(37)

In-service pavements may be subjected to a sequence of construction events. Accordingly, in a network-level LCCA, the asset value of each pavement section at the analysis year is an important parameter required for comparing equivalent treatment strategies. For this analysis, the asset value of the section was assumed to be $250,000. The net present value (NPV) and EUAC are also shown in table 14.

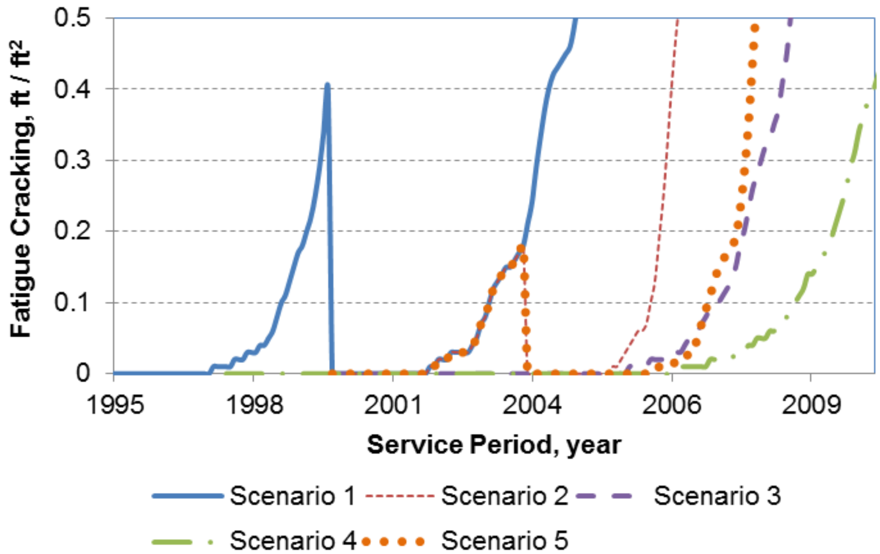


Figure 29. Graph. CalME-estimated fatigue cracking for five treatment scenarios on LTPP test section 06-0505.

Table 14. LCCA for LTPP Section 06-0505 in 1997.

Scenario	Overlay Treatment	Performance Extension from 1997 (years)	NPV of Future Treatment Cost in 1997 ($)	EUAC ($)	Pretreatment Tensile Strain, microstrain (year)	Tensile Strain in 2003 (microstrain)	NPV to Bring the Pavement to State of Good Repair ($)	Revised EUAC ($)
1	Resurfacing in 2000 (current LTPP scenario)	5.8	53,340	59,636	242 (2000)	362	369,466	75,152
2	Resurfacing in 2000 + mill and overlay in 2003	9	290,434	72,685	362 (2003)	162	290,434	72,685
3	Mill and overlay in 2000	10.2	266,699	62,684	242 (2000)	148	266,699	62,684
4	Mill and overlay in 1998	11.8	288,462	58,136	179 (1998)	141	288,462	58,136
5	Resurfacing in 2000 + mill and thicker overlay in 2003	10.2	369,466	75,152	362 (2003)	147	369,466	75,152

Mill and overlay treatments applied in 1998, 2000, and 2003 (scenarios 4, 3, and 2, respectively) yielded different performances, as shown by the performance extension in table 14. Mill and overlay treatment applied in 1998 (scenario 4), when there was little or no surface cracking, yielded the best performance in terms of time extension. Comparing scenario 2 and 3, the latter of the two (mill and overlay in 2000 instead of resurfacing in 2000 and mill and overlay in 2003) is a more optimal treatment sequence. In scenario 2, the AC layer has been significantly damaged by 2003, when the mill and overlay was applied. As such, the delayed mill and overlay (scenario 2) did not perform as well as if it had been applied when the structure was still in good condition, as is the case with scenarios 3 and 4.

Table 14 also shows that the mill and overlay in 1998 (scenario 4), prior to the appearance of surface cracks, is the optimum treatment. When surface distresses such as fatigue cracking are used as the pavement structural indicator, it is difficult to identify the optimum treatment timing because by the time surface distresses appear, the pavement structure may already have deteriorated to a point where lower-level treatments, such as preservation, may not be effective. Accordingly, fatigue cracking can be viewed as a lagging indicator of pavement structural condition, which limits cost-effective alternatives that would otherwise have been possible. Also, the fatigue cracking measured at the pavement surface is effectively covered by any surface treatment and therefore may not be a reliable pavement structural measure in subsequent assessments.

Use of Tensile Strain as Structural Indicator

Structural parameters computed from deflection measurements can be used as leading pavement structural indicators instead of lagging indicators such as surface cracking. Continuous pavement structural evaluations, such as those performed using traffic speed deflection devices (TSDDs) provide an excellent opportunity to identify the optimum treatment that yields the LLCC and thereby leading to more efficient PMSs.[38] Past studies have used curvature indices computed from deflection basins to correlate with the horizontal tensile strain at the bottom of the AC layer (hereafter referred simply as tensile strain).[35,39–46] The correlation was verified on the test section used in this analysis. The CalME computed layer moduli values for LTPP test section 06-0505 were used along with the JULEA program to compute tensile strains and the Surface Curvature Index as a function of time, as shown in figure 30.[37] *Surface Curvature Index* is defined as the difference between the measured deflection at the center of the load and the deflection 12 inches away from the load. A strong correlation between tensile strain and Surface Curvature Index is shown in figure 31.

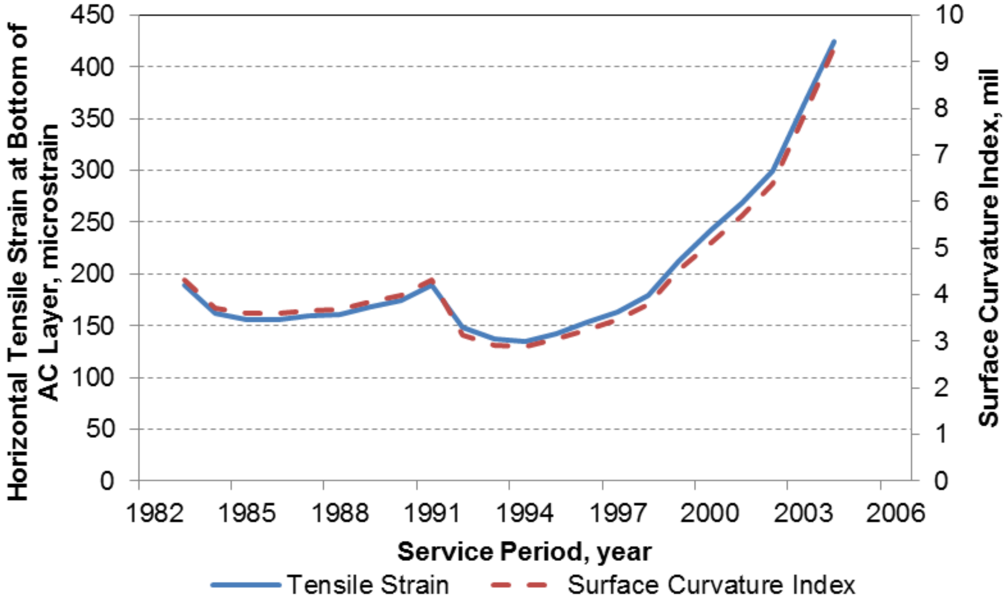


Figure 30. Graph. Tensile strain and Surface Curvature Index as a function of time for LTPP test section 06-0505.

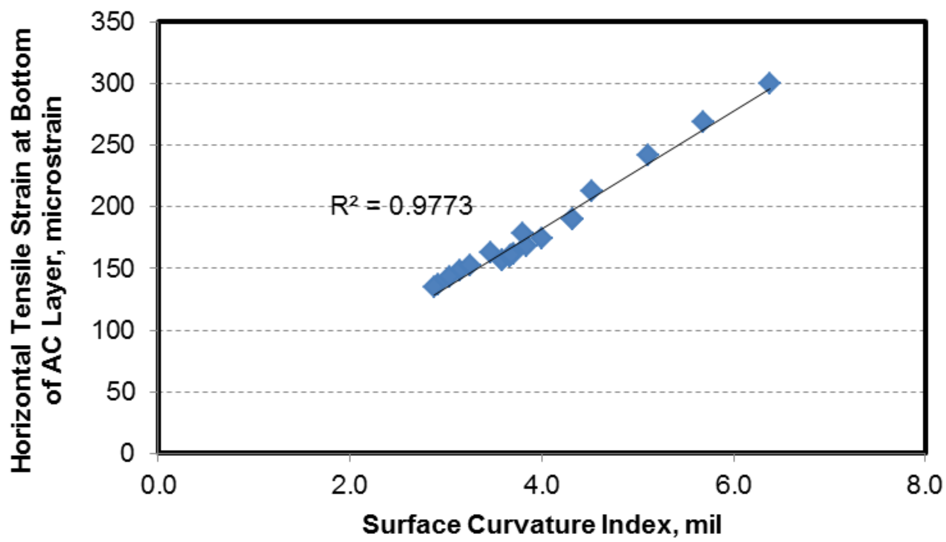


Figure 31. Graph. Tensile strain and Surface Curvature Index correlation for LTPP test section 06-0505.

Figure 32 shows tensile strains as a function of time for the five scenarios under consideration, which were computed using the JULEA program based on the CalME computed layer moduli values.[37] The figure shows that tensile strains can be a structural evaluation parameter that, unlike fatigue cracking, can continue to be an effective structural indicator after surface treatments. Also, the use of tensile strain as structural performance indicator provides continuity in tracking structural condition even after any given M&R activity.

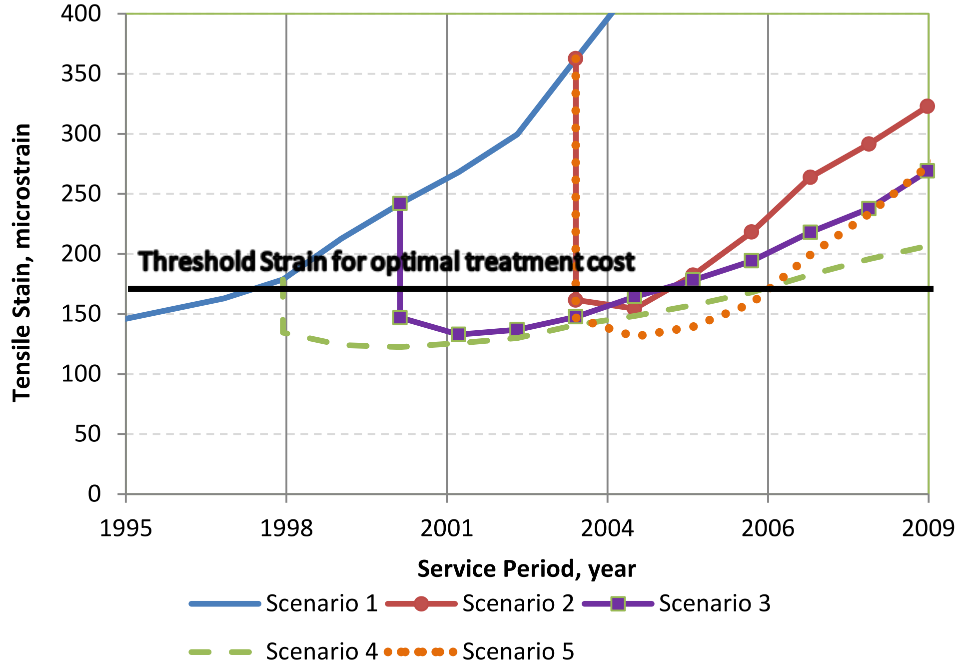


Figure 32. Graph. Tensile strain computed from the CalME layer modulus for different scenarios.

Comparing figure 29 and figure 32, the relative merits of using tensile strains instead of fatigue cracking as a structural indicator are summarized as follows:

- In 1998, the bottom-up fatigue cracking is still not visible at the surface. However, tensile strains show a continuous deterioration from its previous construction event.
- In 2000, the resurfacing treatment (scenario 1) applied to the section reduced fatigue cracking to zero. However, the tensile strains show no improvement in structural condition, as often is the case with preservation treatments. However, the structural rehabilitation (mill and overlay (scenario 3)) applied in 2000 reduced both fatigue cracking and tensile strains.
- In 2003, the reduction in tensile strains is dependent on the thickness of the overlay. Therefore, the effectiveness of treatments can be evaluated with respect to the pavement structural condition at any given time by using tensile strains as a pavement structural indicator.

Reasonable remaining values for pavements at the end of an analysis period can also be computed using tensile strains because they consider the total remaining structural capacity of the pavement rather than using prorated values based on the last treatment. Therefore, in contrast to surface condition measures such as cracking (which are ineffective pavement structural condition indicators once new treatments are applied), tensile strains computed from deflection measurements are able to continuously track the structural deterioration of the pavement system as a whole. This includes contributions from future treatments, including both rehabilitation treatments that add to structural capacity and preservation treatments that often slow down further deterioration.

In the LCCA, tensile strains were used in comparing the five scenarios and in identifying optimum treatment. For the last treatment sequence in each scenario, pretreatment tensile strains and the year of treatment application were also included in table 14. In addition, tensile strain at 2003 (for a 6-year analysis period) was included in the table. Based on EUAC, scenarios 1 and 4 have the lowest cost and would be considered the optimum treatments because both scenarios provide acceptable or above acceptable LOS over the analysis period. However, in 2003, the pavement in scenario 1 would have high deterioration, as shown by the high tensile strain value of 362, while the pavement in scenario 4 would still be in good structural condition, as shown by the tensile strain of 141. Therefore, with a short analysis period (such as 6 years), preventive treatments that have low costs associated with them would be selected, which can lead to rapid deterioration of the pavement structure. Accordingly, for comparison of treatment strategies, it is important to include the remaining value of the pavement or to include the treatment cost that will bring the pavement to a state of good repair at the end of the analysis period. In this LCCA, standardization was obtained by choosing the treatments that produce a pavement with a tensile strain around 150 microstrain at the end of the analysis period. The cost of the thicker overlay required to bring the pavement to such tensile strain level was added to scenario 1, and the revised EUAC is shown in the last column in table 14 for each scenario.

RSI

Comparing the revised EUAC, scenario 4 was found to be the optimum one. Table 15 shows the RSI computed for LTPP test section 06-0505 using the comprehensive LCCA methodology. A similar approach to each pavement section in a network can provide a planned sequence of treatments from which unconstrained budget requirements for PMS can be estimated. Table 15 also includes the RSI for the current treatment scenarios used in the LTPP test section.

Table 15. RSI for LTPP test section 06-0505.

Scenario Type	RSI Preservation (year)	RSI Rehabilitation (year)	RSI Reconstruction (year)
Current	2000	1992	
Optimum		1992, 1998	

Blank cell = Not applicable.

SUMMARY

The following observations sumarize the most important findings and conclusions from the RSI concept validation effort presented in this chapter:

- Continuous pavement structural evaluation provides the opportunity to identify the optimum treatment sequence that yields the LLCC for a given pavement section.
- Use of fatigue cracking as a structural indicator limits the PMS to potentially reactive treatment options and therefore may not lead to the LLCC.

- Tensile strains can be a leading indicator to identify pavement structural deterioration before surface cracks appear. Depending on road classification, threshold tensile strains can be established to select optimal treatment types and timings and maintain the pavement in a state of good repair.

- At the network level, tensile strains are a better parameter to evaluate and track pavement structural condition. A simple and robust correlation between strains and deflection parameters can be used along with performance models to evaluate and predict future performance. For example, the same fatigue damage model used in pavement design can be used in pavement management when tensile strains are estimated from Surface Curvature Index, as demonstrated in this study.

- Treatment sequences evaluated using LCCA should yield pavement in a state of good repair at the end of the analysis period. Longer analysis periods should be used in the LCCA. With a shorter analysis period (such as 6 years), the LCCA could yield preservation treatments (such as resurfacing) that would satisfy the minimum LOS but lead to pavements in poor structural condition at the end of the analysis period.

- The asset value of each pavement section and at each analysis year is required for a comprehensive LCCA at the network level. The need for asset value can be substituted by an approach at the end of the analysis period, the chosen optimum treatment sequence yields tensile strains that are similar to other costlier alternatives.

CHAPTER 5. RSI VALIDATION—MDSHA

INTRODUCTION

In an effort to validate the RSI concept, as well as to understand the implications of implementing the RSI concept at a State level, the MDSHA data, treatments, and performance prediction models were incorporated into the RSI algorithm. The validation of the RSI concept using the MDSHA data was then completed by comparing the results obtained, in terms of treatment costs and condition over time, to the results using the MDSHA approach. This chapter details the approach taken during the validation and describes the results obtained from the validation effort. In general, it was found that the RSI algorithm yielded lower and more consistent yearly treatment costs and comparable yearly conditions when evaluated against the MDSHA approach.

In addition to the results of the validation effort, several other findings are presented in this chapter that are more generalized in nature but are applicable to modern pavement management principles. For example, the effect of time horizons on LCCA results was evaluated using a specific objective function in the optimization, and it was found that the time horizon of the LCCA needed to extend out beyond the analysis period by an amount dependent on the general deterioration characteristics of the pavement network. This research found that the time horizon of LCCA for the MDSHA network should extend out approximately 20 years beyond the analysis period based on the deterioration characteristics of the MDSHA network. This is also due to the fact that remaining value at the end of the analysis period was not adequately and accurately accounted for in the analysis. Also, the construct of genetic algorithms to solve the global optimization problem presented by selecting treatment strategies over longtime horizons, and the use of simulated annealing concepts combined with the genetic algorithms is explored in this chapter.

The RSI concept includes determining optimal M&R strategies as a key step, and, thus, this chapter discusses the selection of an optimization procedure to develop results. The optimization in this chapter included as few heuristics as possible. Essentially, the potential solution space was not limited based on general assumptions such as minimum time between treatments in an effort to ensure that the optimal solutions that were discovered were not limited by many assumptions.

VALIDATION APPROACH

The RSI validation at MDSHA set out to answer the question, “Can the RSI methodology be successfully implemented by a State transportation department using their existing models and processes, and does the implementation of the RSI lead to more optimal decisions?” In order to address this question specific to the MDSHA validation, several steps were taken, and each step is described in detail throughout this chapter. The general steps to the MDSHA validation are as follows:

1. Gather MDSHA data, models, and information about MDSHA processes; all models, costs, and data used in the validation were obtained directly from MDSHA. In addition, several meetings and discussions were held with MDSHA personnel to assure that the project team properly implemented the MDSHA process into the RSI algorithm developed for this project.

2. Implement MDSHA models and data into the RSI algorithm and consider the following.

   - In implementing the MDSHA models and data into the RSI algorithm, several checks were made to ensure that the MDSHA process was followed. In order to complete the checks, the MDSHA system (models and treatment selection criteria) was replicated in Matlab™, and the agreement between the Matlab™ implementation and MDSHA results was assessed.

   - The implementation of the RSI required adopting and enhancing multiple global optimization procedures. The processes used are discussed in this chapter, and the Matlab™ implementation code can be obtained from FHWA.

3. Compare outputs of the RSI algorithm implementation to the current MDSHA process. This comparison was made across many criteria (e.g., yearly costs and condition) and provided the basis for recommendations regarding the RSI algorithm.

4. Develop conclusions and recommendations regarding the implementation of the RSI algorithm at the State level. Several substantial findings were summarized based on the process of implementing the RSI algorithm and the results of the implementation.

The RSI is based on the concept that one single value (e.g., a value representing a remaining life) is not adequate to describe the complete M&R needs of a pavement. A single value is generally not representative of the many possible decision paths that can be followed regarding M&R alternatives, and, thus, an update to the terminology that is representative of more optimal decisionmaking is necessary. Therefore, this validation effort focused on the development of the optimal decision paths and then the comparison of remaining life values in the MDSHA approach to the time until the first treatment in the optimal decision paths in an effort to demonstrate the implications of implementing the RSI concept.

MDSHA Data, Treatments, and Models

An essential part of performing the RSI validation in Maryland was using the data and models currently implemented by MDSHA in their pavement management system. Only changes in procedures (i.e., how the data and models are used) were considered, and no changes were made to model forms and data. The following data obtained from MDSHA were used for this validation effort:

- Treatment types and cost.

- Treatment consequences on each condition metric.

- Treatment selection criteria (e.g., condition ranges that the treatment is allowed to be placed).

- Information on calculating the RSL using MDSHA procedures.

- Deterioration prediction models for each condition metric and functional class.

- Pavement condition data for all of the pavement network, including characteristics of each pavement section (e.g., length and functional class).

MDSHA also provided outputs of several optimization runs using their current pavement management software on the same dataset.

The condition data provided by MDSHA included roughness (IRI), rutting, friction number, two cracking indices, an FCI that combines functional cracks on a scale of 0 (worst) to 100 (best), and an SCI that combines structural cracking on a similar 0 to 100 scale. Upon further conversations with MDSHA, it was revealed that they are in the process of updating their rutting models and did not consider rutting in the optimization runs provided to the project team. Therefore, in order to more accurately compare the RSI validation results to MDSHA results, the RSI module developed on this project did not include rutting.

MDSHA has developed models of expected impacts for each maintenance treatment and each distress measure. For example, each treatment is expected to change the pavement roughness by different amounts, and the change in pavement roughness is a function of the roughness before the treatment was applied. The models for roughness, friction number, and cracking are given in the equations shown in figure 33 through figure 36.[5] The IRI deterioration models account for the treatment type by applying a factor to the exponential function. For example the factor μ in figure 33 changes as a function of the treatment applied. However, deterioration models for FCI and SCI are a function of only age and functional class.

$$IRI(age) = 40 * e^{w*\mu*age}$$

Figure 33. Equation. Progression of roughness as a function of pavement age.

Where:

age = Age of the pavement in terms of years.

w = A factor accounting for functional class and region.

μ = A factor accounting for the last treatment applied (e.g., 1 following reconstruction or thin overlays and 0.9 following micro-surfacing).

$$FN(age) = a * \log(age) + FN_{Initial}$$

Figure 34. Equation. Friction number as a function of pavement age.

Where:

a = A factor accounting for geography and functional class.
FN = The friction number.
$FN_{Initial}$ = The friction number at age zero.

[5]Nathan Moore, email message to author, October 6, 2015.

$$FCI(age) = 100 - b * age \qquad for\ age \le c$$
$$FCI(age) = f - d * (age - c) \qquad for\ age > c$$

Figure 35. Equation. FCI as a function of pavement age.

Where:

f and *c* = The coordinates where the two straight lines that make up the cracking models meet and form a knuckle.

b and *d* = Factors defined by the pavement family that include considerations for functional class, geography, and many other factors,

$$SCI(age) = 100 - b * age \qquad for\ age \le c$$
$$SCI(age) = f - d * (age - c) \qquad for\ age > c$$

Figure 36. Equation. SCI as a function of pavement age.

The MDSHA methodology is based on computation of an RSL. The methodology for calculating the RSL of the pavement is to interpolate values from a table using condition values in order to estimate the number of years until a pavement in its current condition reaches a defined threshold.[6] This threshold is a function of the functional class of the pavement. For example, a pavement section in functional class 1 that has a roughness equal to 145 inches/mi has an estimated remaining roughness life of 8 years. The minimum values of remaining life from each distress are taken as the overall remaining life of the pavement section.

Cost data were obtained for each treatment and in many cases were a function of the condition of the pavement, the class of the pavement (urban vs. rural), the functional class, and the district in which the pavement is located. Finally, 15 treatments were considered in this analysis based on the most updated data provided by MDSHA. The treatments considered in the analysis, along with a general classification of the intensity of the treatments, are shown in table 16. Each treatment shown in table 16 had associated impacts on condition, as well as specific conditions in which it could be placed (e.g., some treatments were excluded in some districts).

[6]Moore, op. cit.

Table 16. Treatments considered for MDSHA validation.[7]

Preservation	Rehabilitation	Reconstruction
• Crack seal. • High-friction surface. • Micro-surface. • Thin overlay (≤ 1 inch of asphalt). • Asphalt patch only. • Surface abrasion.	• Grind-overlay ≤ 1.5 inches: grade increase. • Grind-overlay ≤ 1.5 inch: grade increase, gap graded. • Overlay ≤ 1.5-inch asphalt. • Overlay ≤ 1.5-inch asphalt, gap graded. • Grind ≥ 4-inch overlay. • Overlay > 1.5 inches. • Overlay >1.5 inches, gap graded.	• Reconstruction. • Full-depth reclamation with overlay.

MDSHA Treatment Selection Process

The treatment selection process is the first step in the network-level optimization conducted by MDSHA. The objective of the treatment selection process is to choose the treatment that minimizes agency costs while simultaneously maximizing the extension to the pavement life as defined by MDSHA. The objective function of the optimization followed by the treatment selection process is given in figure 37.[8]

$$Max\, z = \frac{Life\, Extension}{Cost * 0.5 * \left(\dfrac{VMT_{Segment}}{VMT_{Total}} + \dfrac{Lane-Miles_{Segment}}{Lane-Miles_{Total}} \right)}$$

Figure 37. Equation. Objective function used by MDSHA.

Where:

z = The objective function value.

$LifeExtension$ = The extension in the RSL provided by the treatments in years.

$Cost$ = The treatment costs in dollars.

$VMT_{Segment}$ and VMT_{Total} = The VMT for the segment and the network as a whole, respectively.

$Lane\text{-}Miles_{Segment}$ and $Lane\text{-}Miles_{Total}$ = The length in lane miles for the segment and the network as a whole, respectively.

[7]Moore, op. cit.
[8]Moore, op. cit.

The performance extension is calculated as the time from when the treatment is applied to when the pavement RSL returns to the RSL prior to treatment. The RSL is calculated as the minimum of the times it takes each distress to reach a predefined threshold.

An important aspect of the optimization using figure 37 is that a treatment will be selected in all cases where some performance extension can be garnered (i.e., as long as the pavement distresses have deteriorated by some amount). Another attribute is that the value of the objective function creates a measure that can be used to compare many pavement sections. For example, a pavement in poor condition may have a larger objective function value than a pavement in fair condition given the same treatment because the pavement in poor condition will experience a larger performance extension for slightly more costs (assuming similar VMT and lane-miles). However, the objective function does not necessarily promote waiting until the threshold is reached because costs will also be higher for pavements in worse condition. In other words, the objective function value represents a tradeoff between costs and performance extension, where larger values of the objective function is indicative of a more ideal tradeoff between costs and performance extension when compared to other treatment alternatives. This is the basis for the MDSHA network-level optimization; the values of the objective function can be used to prioritize the pavement sections, and then the highest priority pavements are scheduled for final treatment determination.

IMPLEMENTING THE MDSHA PROCESS IN MATLAB™

The basic algorithm for implementing the MDSHA procedure in Matlab™ following the RSI concept is shown in figure 38. The algorithm shown in figure 38 is for the case that a treatment schedule is known and is defined as a vector where each element of the vector represents a treatment choice in a given year. However, the algorithm was developed with this layout so that the structure could be easily modified to the case that the treatment vector was unknown and an optimization module could be input prior to the cost function in order to select the treatment vector. The modification of this algorithm to implement the optimization is discussed later in this chapter.

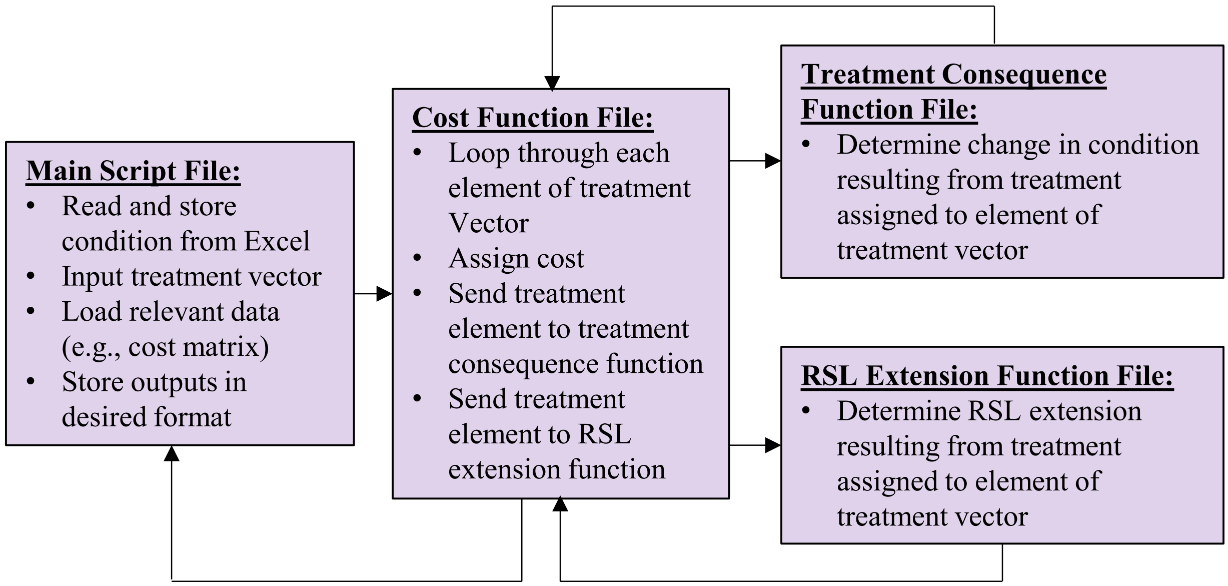


Figure 38. Flowchart. Basic algorithm for implementing MDSHA procedures in Matlab™.

Once the MDSHA approach was recreated and all models and data gathered, comparisons were made between the outputs of the RSI implementation and the outputs supplied by MDSHA. The purpose of these comparisons was to ensure that the MDSHA process was replicated and that all models and costs implemented in the RSI validation code developed by the project team matched the outputs supplied by MDSHA. A subset of pavement sections were randomly selected to verify the implementation of the MDSHA process.

Three types of verifications were conducted to test the agreement between the RSI implementation and the MDSHA results. The first verification was to check that the condition of pavement sections over time matched the information provided by MDSHA for pavements that had no treatment applied. An example of this first verification is shown in table 17 for a sample pavement section, where it can be seen that the Matlab™ RSI implementation matched the values provided by MDSHA. This agreement was consistent in all pavement section samples checked.

Table 17. Example verification results from implementing MDSHA process.

Year	Values from MDSHA					Predicted Values from Matlab™				
	IRI (inches/mile)	FCI	SCI	Rut (inch)	Skid Number	Values on Left				
2014	103.27	92.13	96.52	0.1288	44.00	103.27	92.13	96.52	0.1288	44.00
2015	104.53	89.80	95.68	0.1288	43.93	104.53	89.80	95.68	0.13	43.93
2016	105.81	87.48	94.83	0.1288	43.87	105.81	87.48	94.83	0.13	43.87
2017	107.10	85.15	93.98	0.1288	43.82	107.10	85.15	93.98	0.13	43.82
2018	108.40	82.83	93.13	0.1288	43.77	108.40	82.83	93.13	0.13	43.77
2019	109.73	80.51	92.29	0.1288	43.74	109.73	80.51	92.29	0.13	43.74
2020	111.07	78.18	91.44	0.1288	43.70	111.07	78.18	91.44	0.13	43.70

The second level of verification was to compare the cost and resulting condition of applying a treatment to a pavement section at a given point in time to the results provided by MDSHA. This verification was performed over many pavement sections, and, similar to the first verification, the values produced by the Matlab™ RSI implementation consistently matched the values provided by MDSHA. An example of this type of verification is shown in table 18, where micro-surfacing applied in 2017 was shown to be the optimal treatment.

Table 18. Example of treatment cost validation for pavement section number 5346.

	Distress Values from MDSHA and Matlab™					Predicted Costs from MDSHA		Predicted Costs from Matlab™	
Year	**IRI (inches/mi)**	**FCI**	**SCI**	**Rut (inch)**	**Skid Number**	**Micro-surfacing**	**Thin Overlay**	**Micro-surfacing**	**Thin Overlay**
2014	103.04	86.02	79.98	0.0954	56.50	$62,348	$212,791	Not Calculated	
2015	105.81	83.71	78.32	0.0954	56.34	$64,343	$219,600	$64,343	$219,600
2016	108.64	81.39	76.67	0.0954	56.21	$66,402	$226,627	$66,402	$226,627
2017 (micro-surfacing applied)	117.25	98.95	95.00	0.0954	55.00	$68,527	$233,879	$68,527	$233,879
2018	120.07	97.30	93.35	0.0954	54.39				
2019	122.97	95.65	91.69	0.0954	54.04				
2020	125.93	93.58	90.04	0.0954	53.79				

Blank cell = No cost estimate given because condition of pavement dictates that no treatment is necessary.

The third verification involved performing a treatment selection, in terms of both treatment type and timing, by maximizing the objective function in figure 37 and comparing the treatment selection to the optimization results provided by MDSHA. This verification was performed following a revision of the algorithm shown in figure 38 to include an optimization component. Similar to the first two verifications, the results produced by the Matlab™ RSI implementation matched the data provided by MDSHA. For example, the pavement section shown in table 18 was evaluated using the Matlab™ RSI algorithm, and the algorithm also chose micro-surfacing applied in year 2017 as the optimal treatment. This follows the results obtained from MDSHA.

Implementing MDSHA Data and Models into the RSI Algorithm

Following the implementation and initial verification of the MDSHA approach, the algorithm presented in figure 38 was modified to implement the RSI approach. The modified algorithm incorporated an optimization routine prior to the cost function and reformatted the main script into a function that revised the output of the optimization so that it can be directly used by the remainder of the algorithm. The revision to the algorithm did not affect the MDSHA models and costs that were previously implemented and verified. The revised algorithm that demonstrates the inclusion of the optimization component and the removal of the RSL module is shown in figure 39.

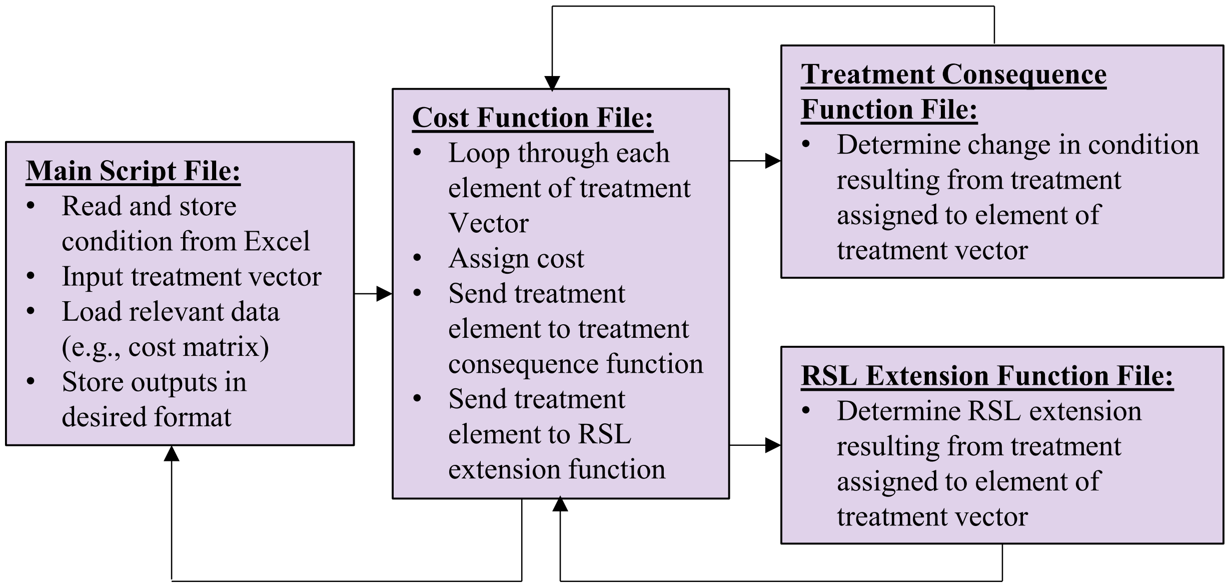


Figure 39. Flowchart. Revised Matlab™ algorithm to include optimization.

In keeping with the approach of the RSI, the objective function presented in figure 37 was no longer used beyond testing the agreement between the Matlab™ RSI implementation and the results provided by MDSHA. Instead, the objective function was changed simply to minimizing total lifecycle costs over the chosen time horizon subject to condition thresholds. The revised objective function is shown in figure 40.

$$Min\, z = \sum_{i=1}^{n} \frac{C(t, iri_i, fci_i, sci_i, skid_i)}{(1+r)^i}$$

Subject To

$$iri_i \le iri_{threshold} \qquad \forall i$$

$$skid_i \ge skid_{threshold} \qquad \forall i$$

$$sci_i \ge sci_{threshold} \qquad \forall i$$

$$fci_i \ge fci_{threshold} \qquad \forall i$$

Figure 40. Equation. Objective function used in RSI validation.

Where:

z = The objective function value.
C = The treatment cost.
t = The treatment type.
i = The index year.
r = The discount rate (taken as 3 percent).
n = The number of years in the evaluation.

The threshold values for each condition measure, which appear in the constraints, were defined as the value for each measure that corresponded to zero remaining life as defined by MDSHA. It should be noted that while computing LCC, the RSI algorithm did not use the remaining value of the pavement section at the end of the analysis period, a limitation that required a long enough analysis period to minimize its effect on LCC comparisons.

Optimization Procedure

The problem construct as shown in figure 40 is discrete, nonconvex, and non-differentiable, all of which are properties required for exact solution methods. In addition, the size of the solution space is too large to conduct a comprehensive search for the optimal strategy. Generally, the solution to choosing the optimal M&R strategy can be viewed as an optimal path problem, and the optimization problem can be constructed based on dynamic programming, which is a method of breaking each problem into several sub-problems that are optimized and then recursively stepping through the problem. However, in the case of this problem construct, the number of feasible paths is very large. Removing constraints (e.g., not defining a minimum time between treatments) results in 16^n possible permutations, where n is the number of years chosen. In other words, if a 60-year time horizon is evaluated, the number of possible permutations is approximately $1.8*10^{72}$. The number of feasible paths can be reduced by implementing rules, such as specifying a minimum number of years between treatments, but a goal of this research was to limit the number of constraints placed on the optimization in order to consider the entire feasible solution space. Therefore, a dynamic programming construct was not considered feasible.

The application of optimization techniques to solve pavement strategy selection has been widely reported in literature. However, the optimization is generally limited to determining the time to place a single treatment or, as is discussed in Sathaye and Madanat, selecting the treatments with the timing defined by thresholds.(47) Medury and Madanat present approaches for selecting strategies using Markov decision processes as a two-stage bottom-up approach using discrete state transitions for performance prediction.(48–50) However, implementing the approach in Medury and Madanat would require significant modifications (e.g., implementing Markov deterioration models) to the models provided by MDSHA, which was not desirable for the RSI validation effort.(49)

Given the construct of the problem, as well as the size of the solution space, it was decided that genetic algorithms were the most promising technique to determine optimal treatment strategies. Genetic algorithms are techniques to solve combinatorial optimization problems in the family of evolutionary algorithms, which are based on the Darwinian concept of survival of the fittest.(50) In genetic algorithms, a combination of values are treated like a chromosome in biology, and the fitness of the chromosomes are evaluated using a fitness function. In the case of this research, chromosomes are a string of numbers representing a given treatment in a given year (e.g., the value of 1 in the fifth position represents do nothing in year 5). The fitness function is the value of the objective function shown in figure 38, and a comparison is made between the chromosomes on the basis of a scaled value of the fitness function. On this project, a rank scaling was used, meaning that the values of the fitness function were ordered from most to least desirable and then assigned a numerical ranking to represent desirability.

The basic concept of genetic algorithms is to mimic evolution to determine the input values of an objective function that produce highly fit outputs. The general approach to the evolution of the solution in genetic algorithms is shown in figure 41. Conceptually, the parent population represents a series of highly fit solutions, and these solutions are then sent through operators that are designed to mimic evolutionary theory to generate a set of offspring. In essence, on this project, the genetic algorithm is used to generate new sets of future streams of pavement improvements at different times that are evaluated against the objective function. The genetic algorithm has the following three main operators as discussed in Surajudeen-Bakinde et al.[(51)]:

1. **Stochastic selection:** Some "elite" parents are chosen for survival to the next generation, and other survivors are chosen with probability based on the scaled value of the fitness function. This ensures some suboptimal survivors exist so that a level of diversity continues throughout generations.

2. **Scattered crossover:** Two parents are chosen to mate, and then a crossover point is randomly chosen so that the next generation is a combination of attributes of the parent generation.

3. **Mutation:** Some members of the parent generation are randomly mutated to form the next generation. This random mutation ensures diversity in the population so that the algorithm is less likely to remain stuck in a localized optimum.

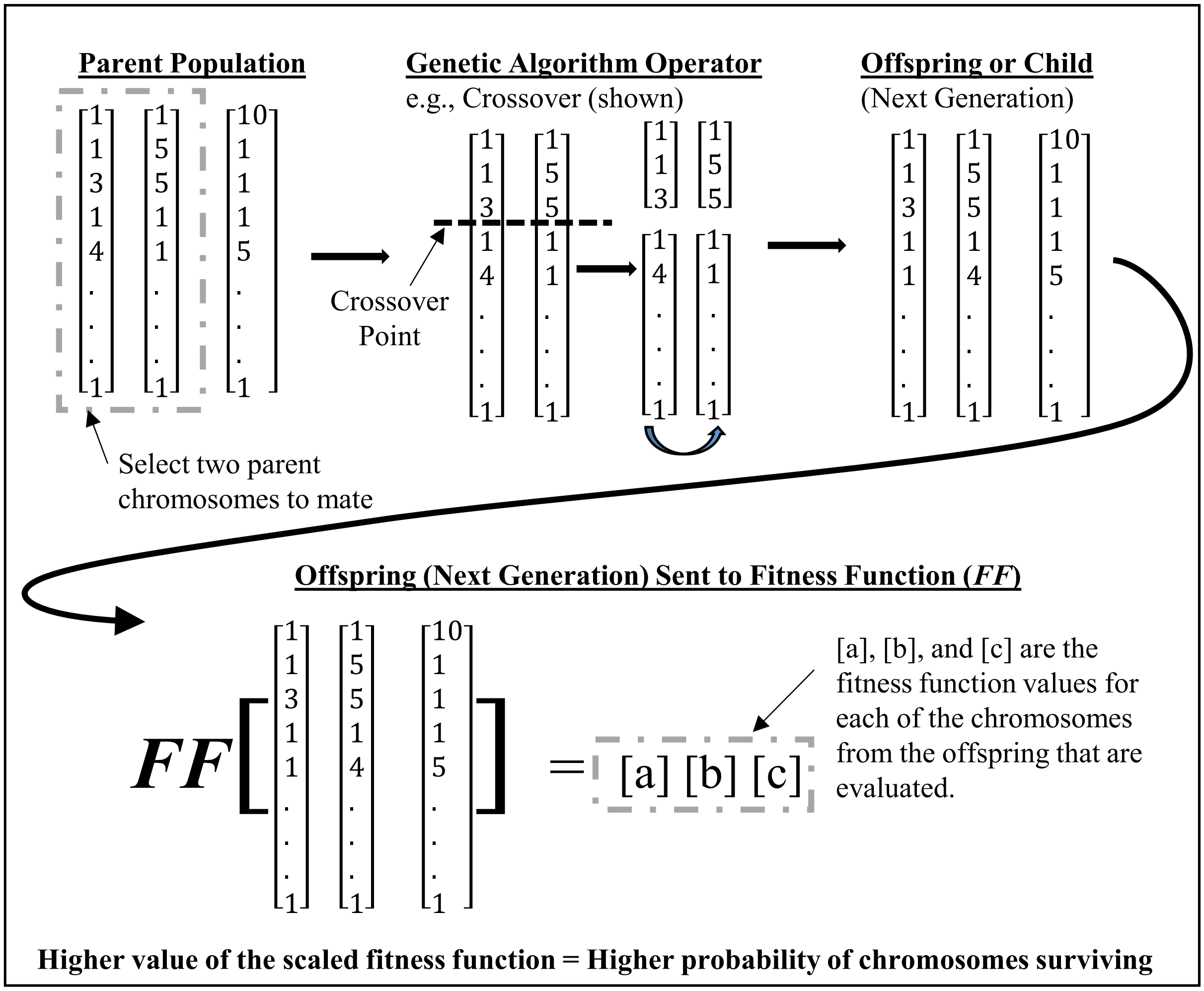


Figure 41. Graphic. Basic flow of chromosomes in the genetic algorithm.

The genetic algorithm procedure was implemented in Matlab™, and the Global Optimization toolbox was selected as the main optimization environment for the RSI validation. The Matlab™ implementation of genetic algorithms was selected because it provided the readily available framework of the genetic algorithm while also allowing the user to manipulate the settings (e.g., mutation rates, fitness scaling, etc.).

The function minimized by the genetic algorithm was the discounted present value of the cost objective function in figure 40. The problem was constructed using integer constraints, and the input to the objective function was a vector of treatments, which is represented as the values of *t* in figure 40. The vector of treatments was constructed such that a value of one represented the do-nothing condition, and then integers were assigned to each treatment. The location of the number within the vector represented the year that the treatment was applied. For example, the vector [1 1 1 5] is representative of no M&R for the first 3 years and a thin overlay applied in year 4. This vector is what the genetic algorithm manipulated to find solutions for the objective function in figure 40.

The constraints shown in figure 40 were set up as penalty values for the value of the objective function. The condition metrics (IRI, skid number, SCI, and FCI) were evaluated at each step in time, and if the constraints were violated, the treatment cost was assigned a cost of 10^6, which is much higher than any expected treatment cost for the pavement. The penalty value was evaluated during the development of the optimization procedure, and it was found that the value of the penalty had a strong influence on whether the optimization reported local optimums or converged to a global optimum. Higher values for the penalty resulted in more local optimums reported. This is because larger differences in fitness function values result in a lower probability that the parent associated with the worse fitness score will be carried on through future generations. In other words, once a local optimum is discovered, the genetic algorithm converges on it much more rapidly for higher values of the penalty assigned for violating the constraints.

The initial population input into a genetic algorithm is an important parameter because it has an effect on computational efficiency and the convergence towards a globally optimal solution.(52) Essentially, there is a tradeoff between computational time and the ability of the algorithm to consistently converge on the same optimal value. In order to address this, several trials were conducted in order to determine how to best construct the initial population. These trials consisted of varying the size and characteristics of the initial population and running several loops of the same optimization in order to determine which set of characteristics of the initial population led to the fewest variations in solutions. The final selection of the initial population was set so that each optimization had a mixture of standard initial inputs and random initial inputs.

The genetic algorithm procedure implemented in Matlab™ allows for the following two options when generating an initial population for the optimization:

- A randomly developed initial population.
- A user-specified initial population.

For this project, it was determined that the best initial population consisted of mixing the two options. A total of 62 strategies were developed that represented possible optimal solutions for various permutations of initial pavement conditions. For example, it was conjectured that a pavement with very high age, high IRI, and high cracking would best be suited by a strategy calling for reconstruction in the first year followed by preservation in 8-year intervals. Although this may be a reasonable strategy, it may not be always an optimal strategy for all pavements with a poor initial pavement condition. The genetic algorithm uses the initial strategies in the initial parent generation to create future combination of treatments to be evaluated that trend toward a more optimal combination of treatments. In addition, it was expected that the optimal strategy for any given pavement will include more values equal to one (do nothing) than values that are greater than one. This was specified in the initial population. Finally, 38 random strategies were specified to be created by Matlab™, and the random strategies changed in every iteration of the optimization.

Given the stochastic nature of the genetic algorithm, optimality cannot be guaranteed. However, several steps can be taken to promote certainty that a global optimal solution is found. One characteristic of the optimization problem that affects whether the genetic algorithm converges on local optimums or the global optimum is the topography of the solution space. In other words, the change in the fitness function values for each potential solution affects whether the final solution is more likely to be a global optimal or a local optimal. To illustrate this, two potential representations of the solution space topography are shown in figure 42. The topography represented in figure 42a contains clear minima that are consistent, and the topography represented in figure 42b contains minima hidden in a considerable amount of noise. Given that global optimization can be viewed as a hill climbing problem where the topography of the solution space effects the response of the algorithm, the solution space represented in figure 42a is more conducive to a genetic algorithm more consistently finding the global optimization, assuming that an adequate population is specified to spread across the solution space. It is expected that by treating the constraints as a penalty on the cost and making the penalty consistent (i.e., not dependent on the characteristics of the pavement), the solution space of the optimization in the RSI validation is more closely represented by figure 42a.

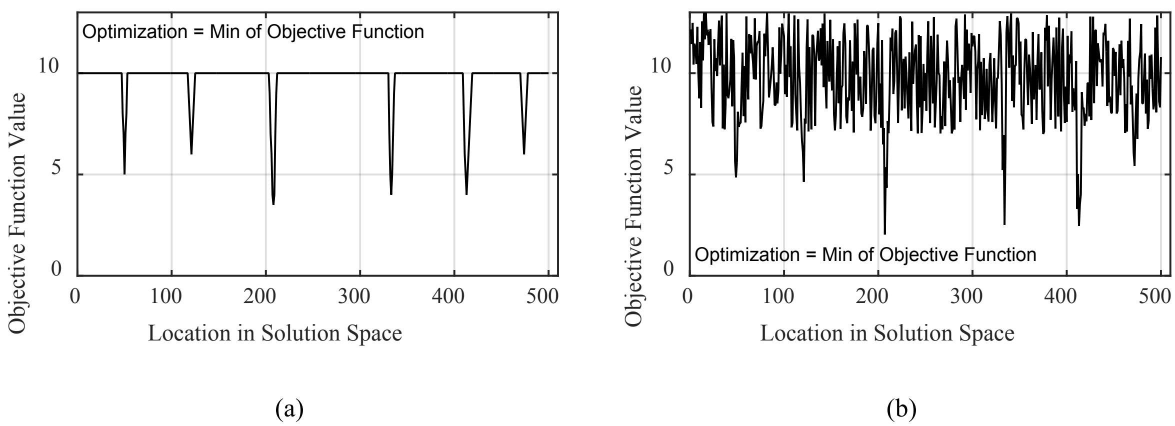


Figure 42. Graphs. Comparison of solution space topographies with different complexity.

Another approach to ensuring that a global optimum is reached is to add diversity into the population once the algorithm begins to converge on a solution. The added diversity causes the population to expand across the solution space. Instead of using functions within the genetic algorithm toolbox in Matlab™ to perform this, the algorithm used for this project was modified to add diversity at specified times and also to incorporate principles of another global optimization procedure known as simulated annealing. Simulated annealing is an optimization procedure designed to mimic the metallurgical process of annealing by essentially starting with a large number of potential solutions and then randomly perturbing the solutions and selecting a certain number to carry through to next steps with some changes.(53) The criteria that specifies whether a solution is carried forward in simulated annealing is defined by an acceptance probability function, and the number of solutions carried forward decreases over time. The acceptance probability function places a higher probability that more desirable states are carried through the solution but also maintains a probability that some less desirable states survive to maintain diversity. Essentially, in the first steps, the potential solution space is searched broadly, and then, as specific potential solutions are identified, the population carried forward is forced to reduce toward optimums within the solution space.

Using the basic principle of simulated annealing, as well as the concept of added diversity in genetic algorithms, three levels of loops were set up to solve the genetic algorithm in this project.

In the first level, the initial population was large (100 streams of alternative improvement scenarios (chromosomes) consisting of 62 specified and 38 random), and the stopping criteria was less strict (i.e., the relative change in the fitness function was allowed to be higher than the final level). This level was solved through eight loops, and the solutions were stored. The solutions to the first eight loops were used to create a new population by manipulating these first solutions. The manipulations included shifting the chromosomes and artificially adding values of one in place of treatments. Upon studying several solutions from the first level of the algorithm, it was found that several treatments were more optimal if they were shifted in time (e.g., a micro-surfacing is more optimal in year 5, but the algorithm recommended it in year 4). This is indicative of the algorithm becoming stuck in local optimums, and thus, the manipulations were designed to address this shift in time.

The second level included the manipulated solutions from the first level as well as several randomly generated solutions to create a smaller initial population (on average between 50 and 60). The second level was looped three times and the solutions stored. Finally, the third level included manipulating the solutions in the second loop and adding some random diversity to create a much smaller initial population (approximately 20), and the genetic algorithm was run once more with more strict stopping criteria than the first two levels. Although this overall process was very computationally intensive, it produced results that were consistent and provided higher assurance that the globally optimal solution was identified.

Problem Construct

Once the genetic algorithm was calibrated to produce consistent solutions that were expected to be the globally optimal solutions, the MDSHA data were incorporated into the algorithm. Only asphalt pavements were considered in this analysis, although the algorithm could be easily modified to consider rigid and composite pavements. Asphalt pavements represent the majority of pavement sections in the MDSHA network. This section of the chapter presents the methods used to select the sample of pavements, the method for using cloud computing applications to solve the RSI optimization, and the analysis period for the LCCs.

Sample Selection

From analyzing the MDSHA optimization results, their analysis was performed on 3,082 unique segments. Of these segments, 204 were already scheduled for work before 2017 (i.e., these are not in the optimization). Of the remaining 2,878 unique segments used in the optimization, 1,716 were identified as flexible pavements, and 1,653 of the flexible sites had complete 2014 datasets. After evaluating the required computational costs of performing a 40-year strategy selection optimization on each of the 1,653 segments, it was determined that although it was possible to analyze all segments, the best approach would be to select a representative sample from the 1,653 segments on which to perform the optimization.

In order to determine whether a sample could be selected so that it represented the MDSHA flexible pavement network, an optimization algorithm was devised so that the objective was to minimize the number of sites selected given some constraints. The constraints were based on the results of the two-sample Kolmogorov-Smirnov test, which is a nonparametric test used to compare two distributions. Thus, it was chosen to compare the selected sample to the initial population. Eight factors were chosen to describe the characteristics of the network: district, functional class, AADT, IRI, initial FCI, initial SCI, initial rutting, and initial skid number values. The constraints were set up so that when the selected subset was compared to the initial population, the results of the two-sample Kolmogorov-Smirnov test (with an α of 0.01) indicated that the null hypothesis of the two samples coming from the same distribution could not be rejected. Finally, it should be noted that any covariance between the selected characteristics was neglected for the sake of this sampling. However, a level of correlation does exist between the characteristics (e.g., a higher initial functional cracking is likely to also correspond to a higher initial structural cracking).

The results indicated that the network could be adequately represented using 338 unique pavement sections. The cumulative histograms were compared for the sample of 338 and the initial population of 1,653, and the results are shown in figure 43. It can be concluded from this figure that the selected sample is representative of the larger population and that only 338 segments are required to represent the initial population.

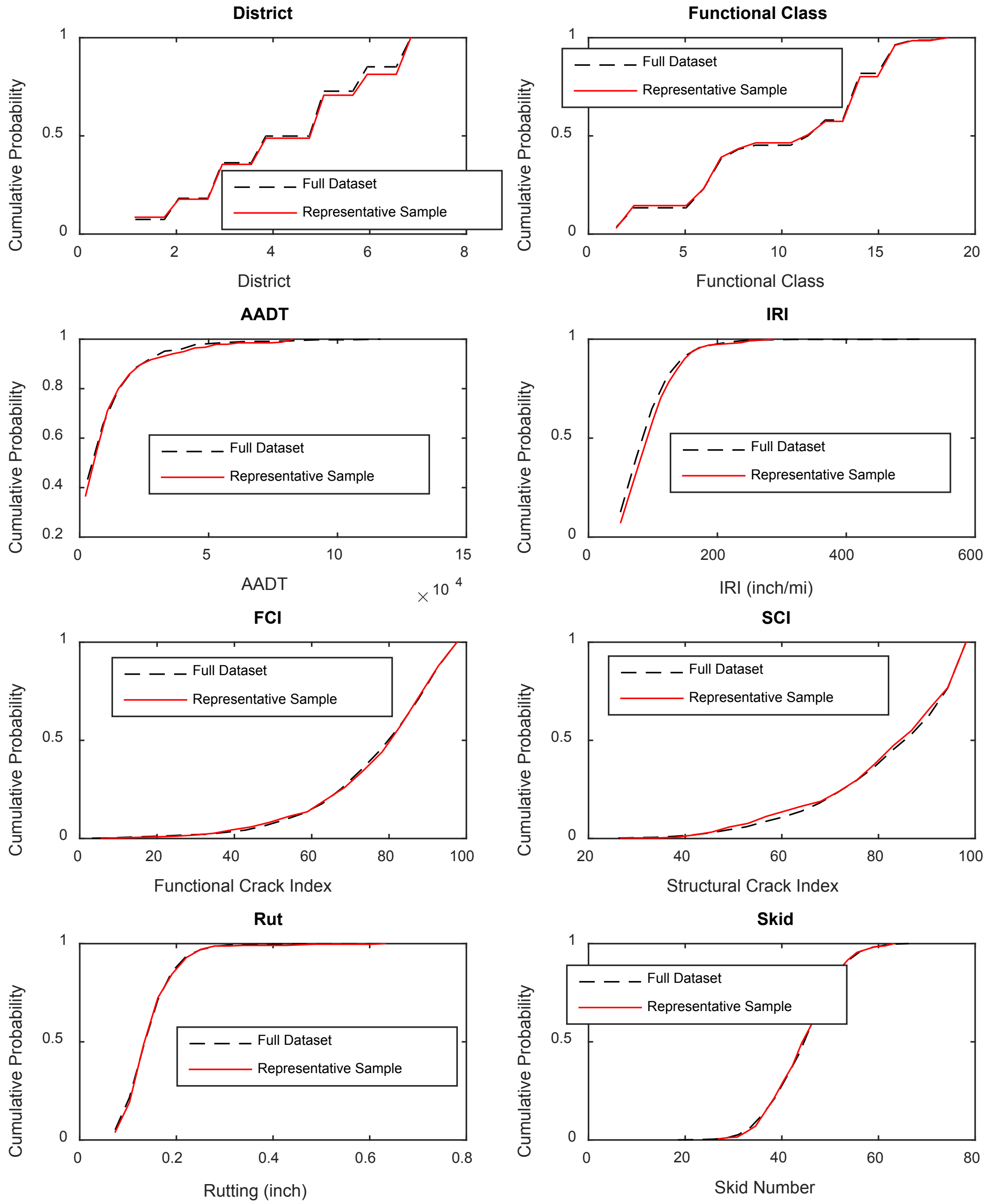


Figure 43. Graphs. Comparison of the sample set characteristics of the initial population to the chosen sample.

Cloud Computing Application

The genetic algorithm can be a very computationally intensive optimization approach, and the setup of the process as described earlier in this chapter increased the time required to converge to optimal solutions. Therefore, it was determined that solving the genetic algorithm for 338 pavement sections over varying analysis periods was not feasible on a single computer.

Instead, parallel computing strategies and cloud computing applications were required to solve the optimization within the project time constraints.

Parallel computing includes separating independent pieces of a calculation and sending the separate pieces to different processors within either the same or separate computers. Sending the parallel calculations to processors in separate computers is essentially the concept behind cloud computing. For example, it was described earlier how several loops were incorporated into the optimization algorithm, and each of the loops within a single level are independent of each other. Thus, each of these loops can be run in parallel on separate processors.

In order to apply these concepts to the RSI validation effort, the Parallel Computing toolbox in Matlab™ was incorporated into the algorithm. The parallel processes were sent to virtual workers in the Amazon Web Services® environment, and the solutions were returned and stored on a local computer. It was found that by using the cloud computing applications, the time required to develop optimal solutions was decreased by a ratio of approximately 15:1.

Analysis Period Selection

In order to assess the effect of the time horizon on the optimal strategy selection, the optimization analysis period (*n* in figure 40) was set to 20, 40, and 60 years. Given the specific objective function (minimizing lifecycle costs without including remaining value), the effect of the analysis period can be significant depending on the specific characteristics of the pavement network (e.g., deterioration rate). It is important to note that it is expected that the effect of the analysis period would be mitigated if a salvage value is applied at the end of the analysis period. For example, the objective function in figure 40 dictates that the most optimal solution is not to apply a treatment if the constraints are not violated. If a salvage value was applied (e.g., as a negative cost in the objective function), then a lowest lifecycle cost alternative would be expected to result in a better condition at the end of the analysis period. In the case of the objective function used in this validation, a short analysis period would result in no treatment applied to a significant portion of the pavement network and a worsening of the average pavement condition toward the end of the analysis period.

Once the optimization was completed for all three analysis periods, the resulting average network condition was compared. The average network roughness for all three analysis periods is shown in figure 44, the average network SCI is shown in figure 45, and the average network FCI is shown in figure 46 as a function of time. Several significant trends emerged when comparing the analysis periods, and these can be seen in figure 44 through figure 46. First, in each case, the first 10 years of the analysis produced relatively consistent results. This time period is heavily influenced by the initial condition of the pavement network, and some of the constraints required early treatments selection based on the initial condition. For example, micro-surfacing was not allowed on very poor pavements (based on the models and business rules supplied by MDSHA), and thus, the initial conditions of the network dictated which pavements could be selected for micro-surfacing.

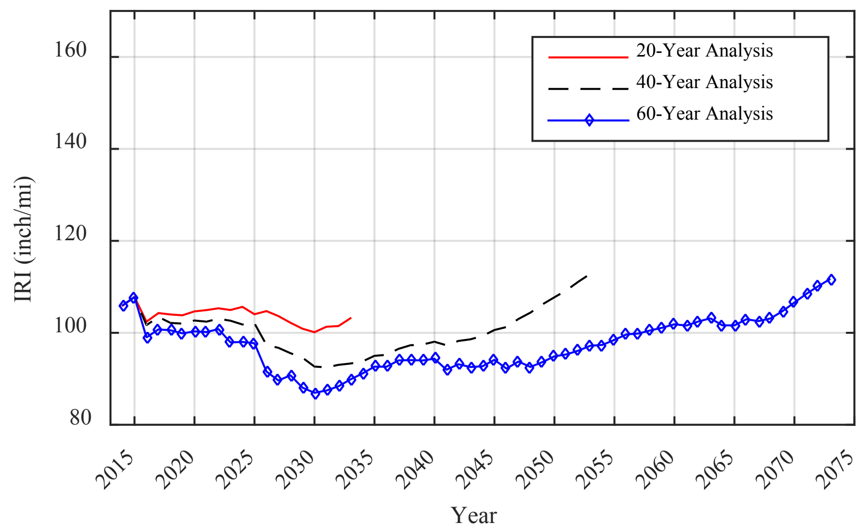


Figure 44. Graph. Average network roughness for three analysis periods.

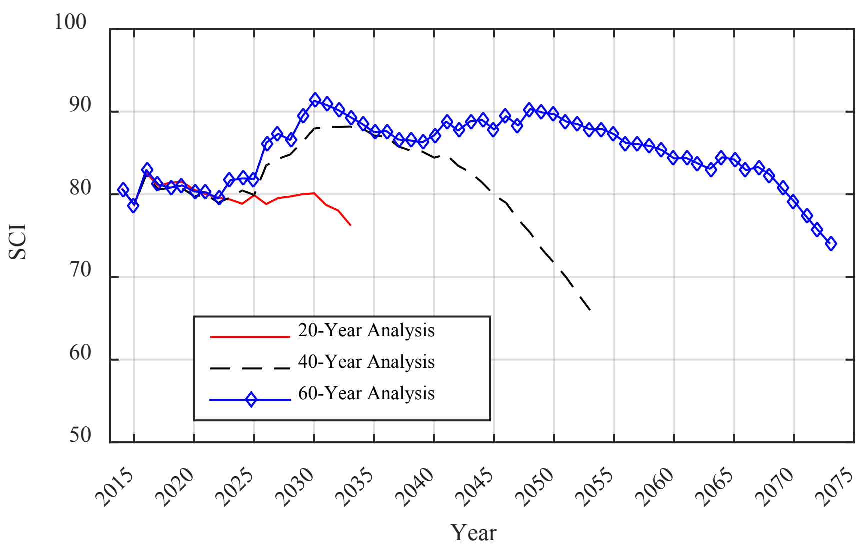


Figure 45. Graph. Average network SCI for three analysis periods.

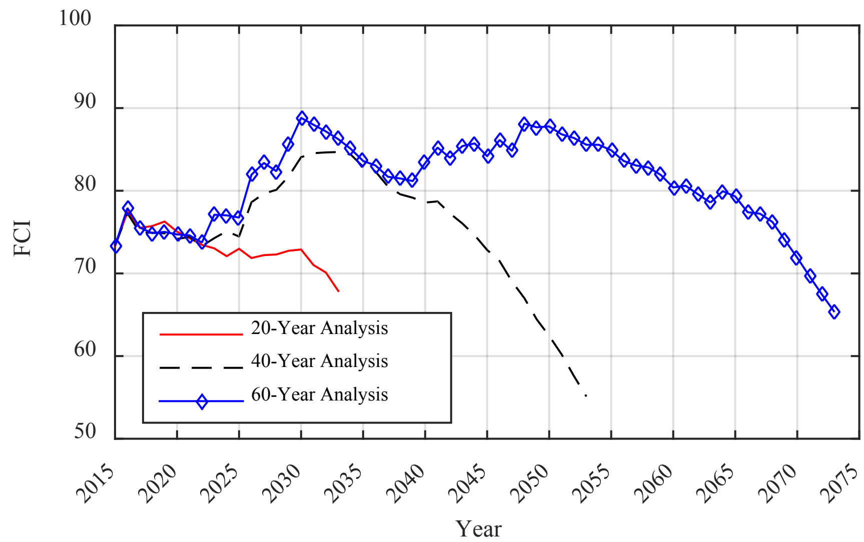


Figure 46. Graph. Average network FCI for three analysis periods.

Another observation to be made from the trends seen in figure 44 through figure 46 is that there is a time horizon when the pavement condition begins to deteriorate. This occurs approximately during the last 20 years for the 40- and 60-year analysis period. This time horizon is driven by the objective function, and in the case of this validation, a salvage value was not included in the lifecycle cost calculations. As described earlier, the lowest cost option is to do nothing as long as the constraints are not violated, and thus, pavements that were maintained in good condition over the initial portion of the analysis period will be allowed to deteriorate over the latter portion.

There is a time period when the pavement condition is stable and consistently maintained in good condition. This occurs at between 2030 and 2035 in the 40-year analysis and between 2030 and 2050 in the 60-year analysis. It has been proposed in pavement management that the lowest costs are realized when the pavement network is maintained and preserved in good overall condition, and this stable time period appears to support this hypothesis.

Based on the comparisons between the three time horizons, it was determined that the RSI validation effort would be conducted using the first 20 years of the 40-year analysis. By selecting the first 20 years of the 40-year analysis, the effect of the length of the analysis period on the optimization results was minimized while also including a significant time frame for comparisons. In addition, this was selected because the comparison against the MDSHA results are limited to only the first six years of the analysis period.

RESULTS

The results of the RSI implementation were compared to the results from the MDSHA analysis in terms of the yearly costs, work type, and condition metrics (IRI, SCI, FCI, and skid number). Although the time horizon and objective functions from the two approaches are different (see figure 37 and figure 40), it is expected that if the RSI methodology represented a valid approach, then the RSI methodology would lead to consistent prediction of treatment needs, performance, and costs over the analysis period. Finally, it is important to note that the results are comparing optimal strategies for each pavement section (i.e., an unconstrained analysis), which is the first step in a bottom-up network optimization approach. The next step in a network-level optimization would be to select the pavement sections that would receive work in a given year to address budget constraints, and this optimization would be performed on a yearly basis.

When comparing the yearly costs (figure 47), the same trend was seen for the first 3 years, with the large costs in the first year representing the accumulated backlog. Recall that the work for 2015 and 2016 had already been scheduled, and, thus, the optimization begins in 2017 using the 2014 condition data. The 2018 cost from the RSI validation is very low (approximately $25,000 USD), and the costs begin to stabilize in 2019. The 2020 costs from the MDSHA approach are very high and include many sites in which the optimal choice would be to defer M&R activity past 2020. However, the form of the MDSHA objective function (see figure 37) dictates that practically every pavement section will have work recommended within the specified time horizon, which was 6 years (2015 to 2020) according to the MDSHA data. It is important to note that the MDSHA optimization approach is a biennial process, and the last 2 years of the optimization are not scheduled for work. In other words, a 6-year time horizon is evaluated in order to develop treatment schedules for the third and fourth years.

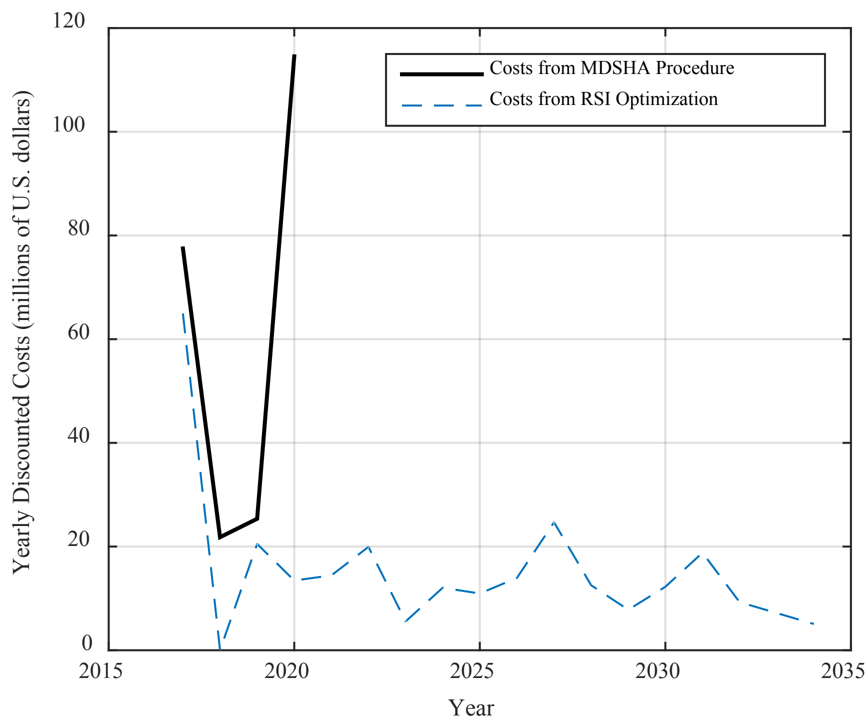


Figure 47. Graph. Comparison of yearly M&R costs.

For both RSI and MDSHA procedures, the mix of identified work types—do nothing, preservation, and rehabilitation—were compared (in figure 48 to figure 50), and in both procedures, much more work was recommended in 2017 than in either 2018 or 2019. It was found that the treatments in 2017 are heavily dictated by the 2014 condition irrespective of the optimization procedure. In other words, the treatments that can be selected for given pavement sections are constrained by the initial condition. There was very little agreement in the 2018 through 2020 mix of work types for preservation (figure 49) and rehabilitation (figure 50) (although the trends were similar for years 2017 through 2019). The MDSHA procedure did not recommend reconstruction, and the RSI validation approach had 9-percent reconstruction in 2017 and 13-percent reconstruction in 2020.

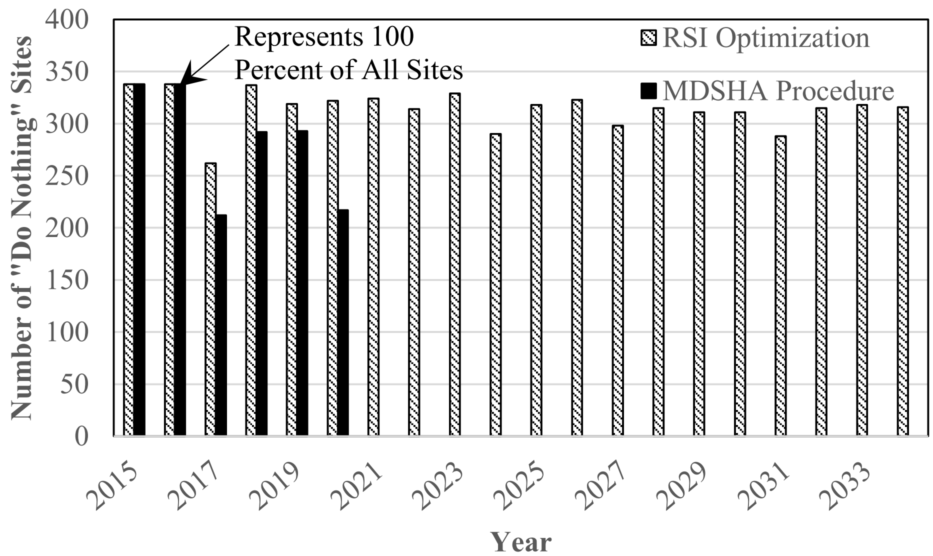


Figure 48. Graph. Recommended do nothing sites per year.

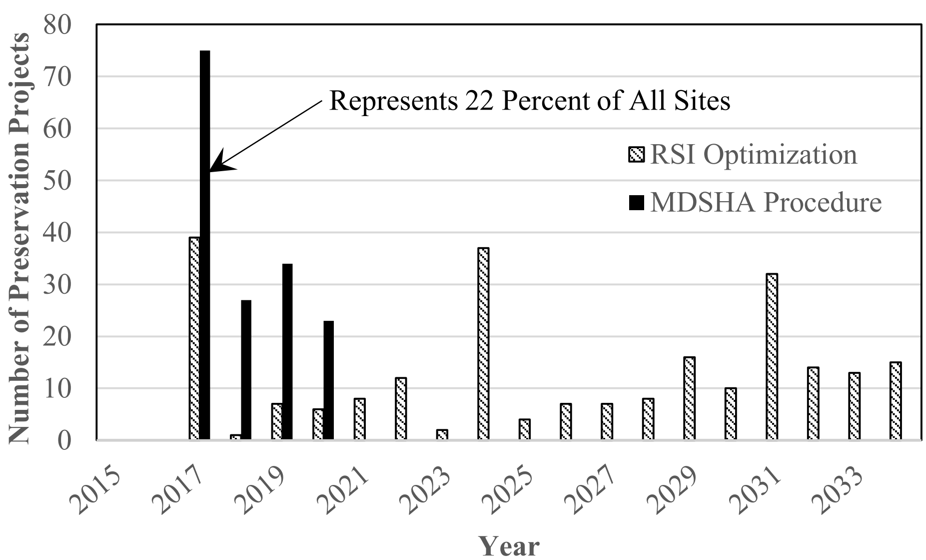


Figure 49. Graph. Recommended preservation work per year.

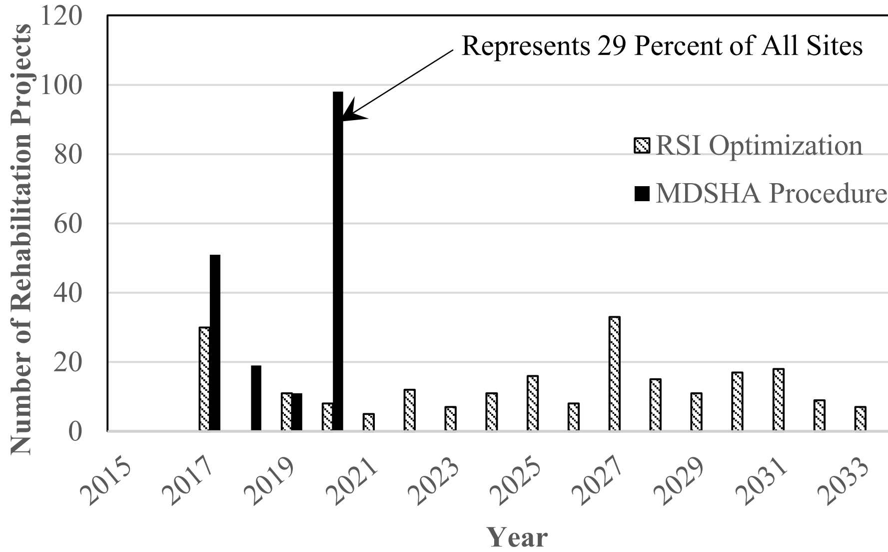


Figure 50. Graph. Recommended rehabilitation work per year.

The resulting condition based on the MDSHA procedure and the RSI process was compared in terms of IRI, FCI, SCI, and skid number in figure 51 to figure 54. Similar to the yearly costs presented in figure 47, the MDSHA process resulted in a significant improvement in the measures in year 2020, which is a result of the specific objective function used to select treatments. The MDSHA process results in a slightly better condition in each case. However, in the long term (approximately 15 years), each measure resulting from the RSI optimization matched the 2019 values from the MDSHA process. In other words, the RSI optimization procedure leads to a consistent prediction of treatment needs, performance, and costs over the analysis period.

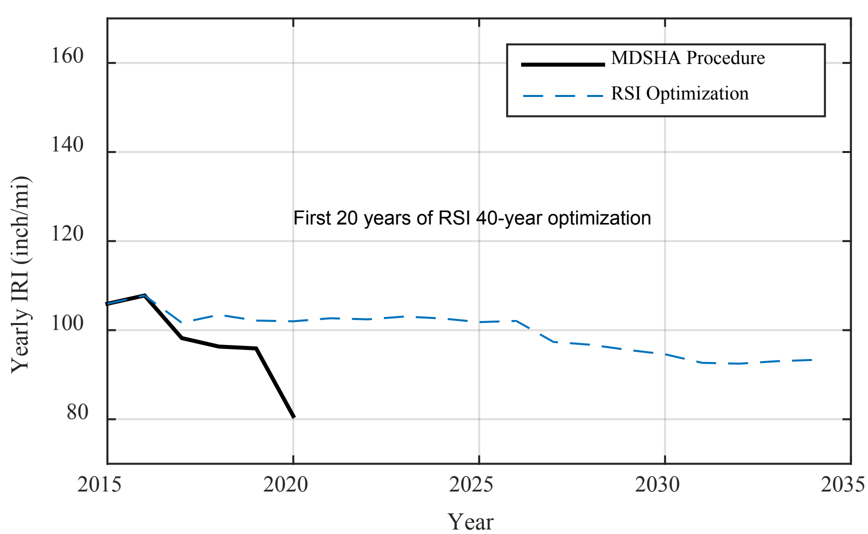


Figure 51. Graph. Average network roughness resulting from MDSHA and RSI approaches.

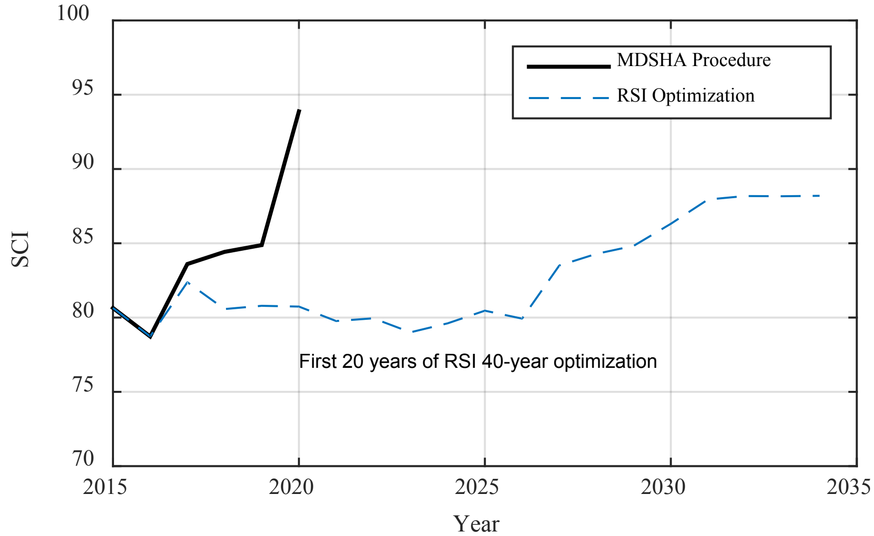


Figure 52. Graph. Average SCI resulting from MDSHA and RSI approaches.

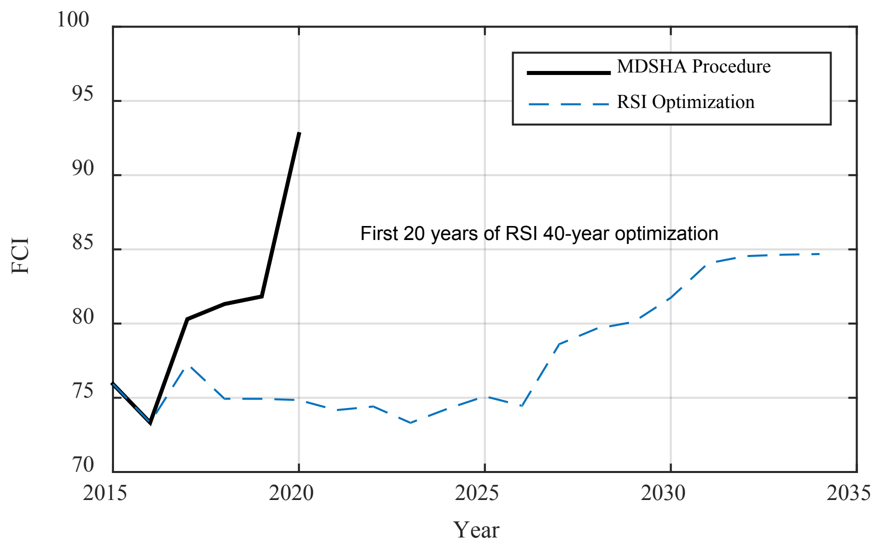


Figure 53. Graph. Average FCI resulting from MDSHA and RSI approaches.

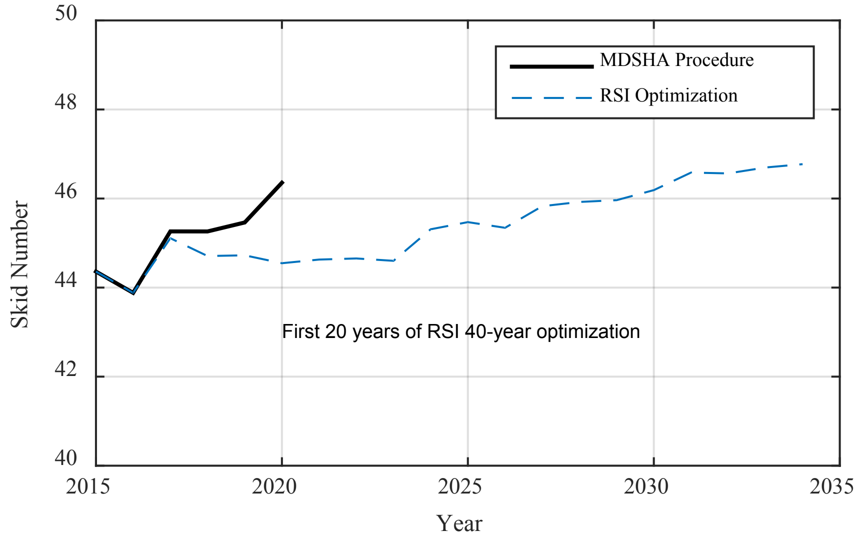


Figure 54. Graph. Average skid number resulting from MDSHA and RSI approaches.

The average pavement roughness resulting from both the RSI and MDSHA approaches is shown in figure 51. For the RSI optimization, it can be seen that the roughness remained relatively steady over the first 11 years and then began to decrease steadily over time. This relatively steady time frame of approximately 10 years was present in each condition metric and was also present in the three time horizons evaluated (20, 40, and 60 years). The SCI (figure 52), FCI (figure 53), and skid number (figure 54) demonstrated the same behavior as the roughness. It should be noted that an improvement in the skid number, FCI, and SCI is demonstrated by an increasing value, whereas an improvement in roughness is signified by a decrease in the value.

Figure 55 through figure 57 show the IRI, SCI, and FCI, respectively, at the time of preservation for both the MDSHA and RSI approaches. Any work recommended in 2020 for the MDSHA approach was not included in these figures given that the time horizon (6 years) used in the MDSHA approach significantly affected the 2020 results as discussed earlier. For each measure, preservation is recommended when the pavement is in better condition for the RSI optimization than for the MDSHA procedure. According to the MDSHA data provided, two sites were exempted from the constraints for the preservation treatment set at IRI threshold of 170 inches/mi by MDSHA models. However, the RSI optimization placed constraints on the condition ranges for which preservation was allowed (based on MDSHA provided models).

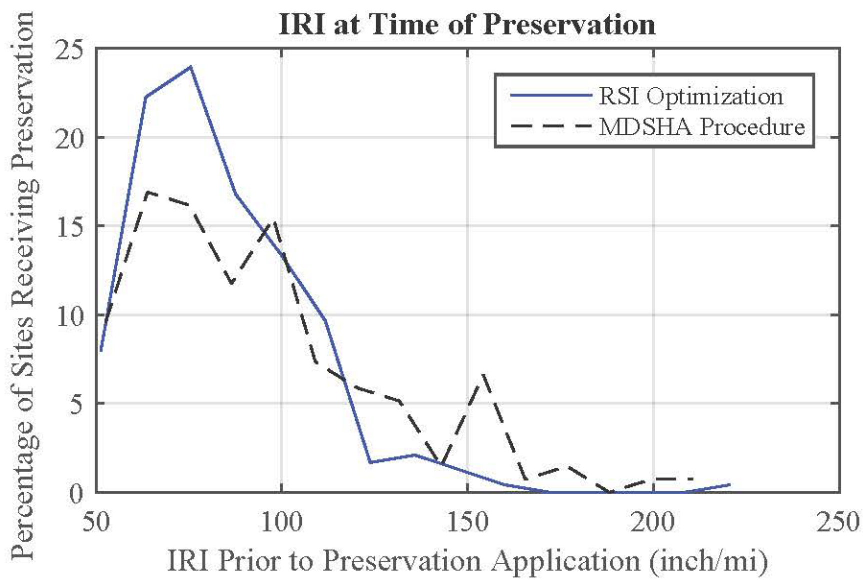


Figure 55. Histogram. Pavement roughness at time of preservation.

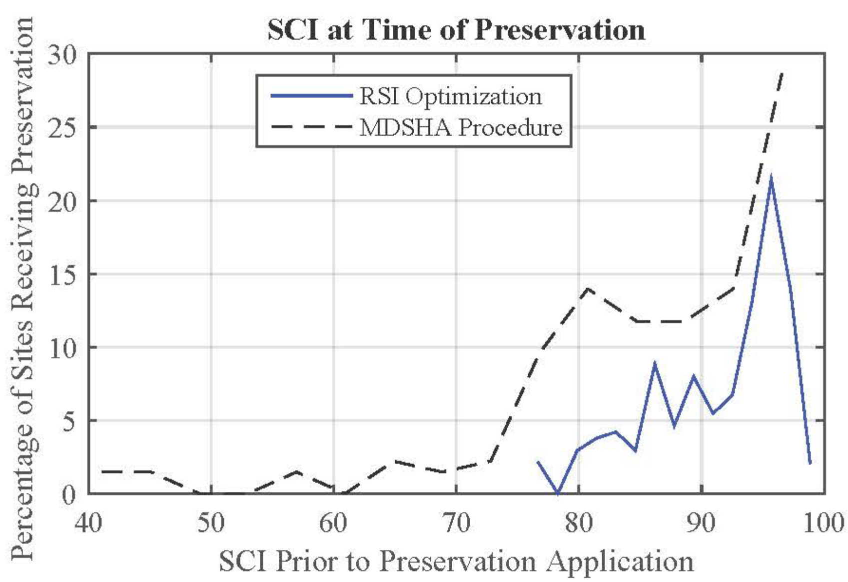


Figure 56. Histogram. SCI at time of preservation.

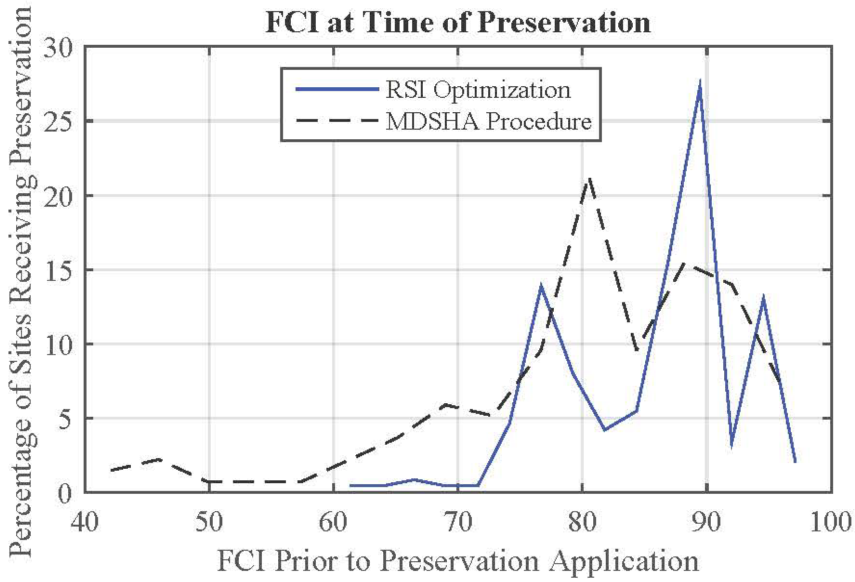


Figure 57. Histogram. FCI at time of preservation.

Figure 58 through figure 60 show the IRI, SCI, and FCI, respectively, at the time of rehabilitation for both the MDSHA and RSI approaches. Contrary to the findings of the average condition when preservation was recommended, the average value for each measure when rehabilitation was recommended represented worse pavement condition for the RSI optimization than for the MDSHA procedure. In other words, the RSI optimization generally recommended that preservation be applied on pavements in better condition, and rehabilitation applied on pavements in worse condition than the MDSHA procedure. This is an expected outcome given that the FCI and SCI were the two measures that mostly triggered M&R, and rehabilitation effectively resets the FCI and SCI values back to 100 irrespective of the initial pavement condition.

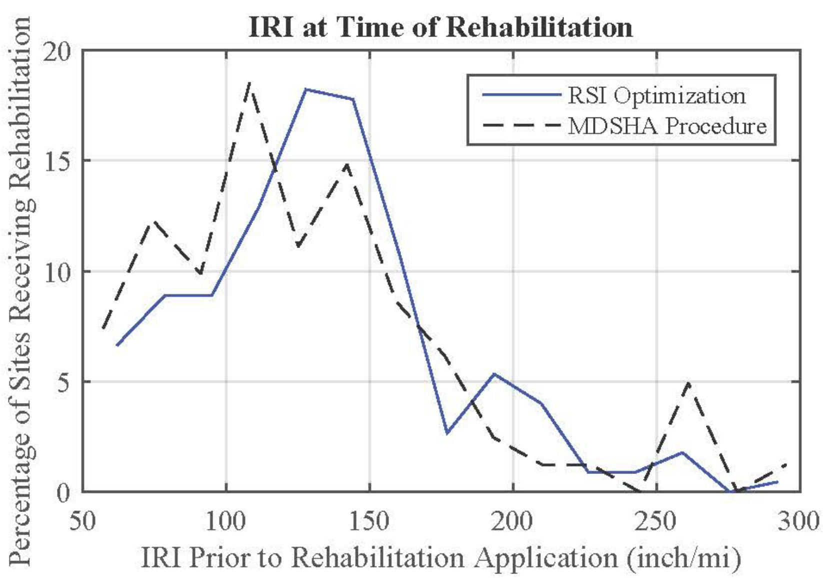


Figure 58. Histogram. Pavement roughness at time of rehabilitation.

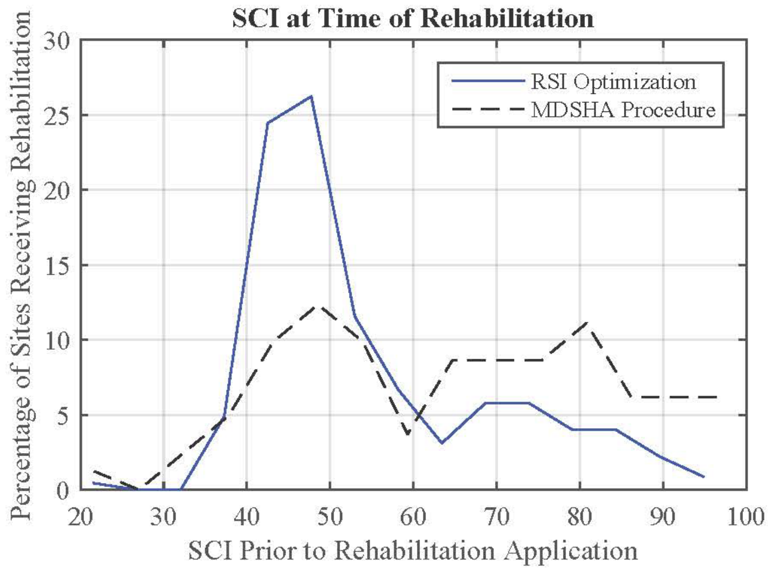


Figure 59. Histogram. SCI at time of rehabilitation.

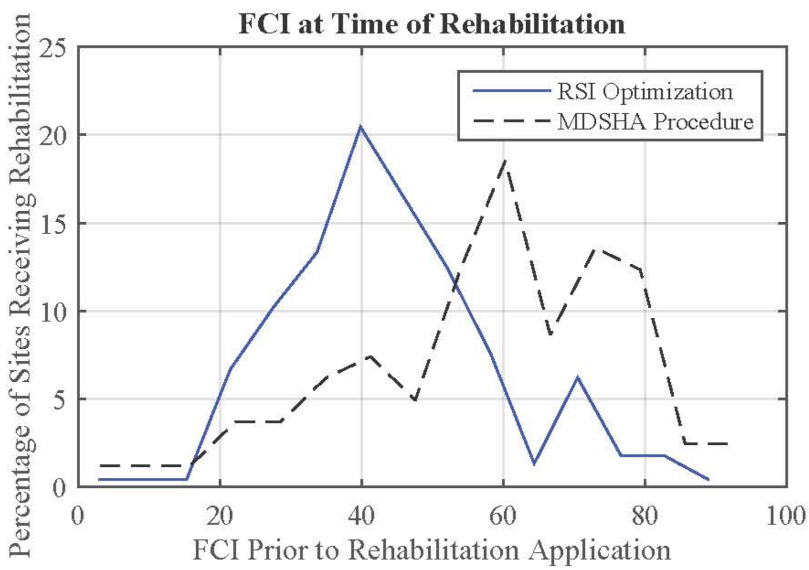


Figure 60. Histogram. FCI at time of rehabilitation.

Linking the MDSHA PMS Process and RSI Concept

The RSI concept is based on the idea that pavement's M&R requirements cannot be defined by a single value representing the end of life of the pavement. Instead, pavements should be described based on intervals used to communicate the amount of time before a treatment type is required to provide acceptable or above acceptable LOS at the lowest practical LCC. Implicit in this change in terminology is the idea that describing a pavement using service intervals more closely reflects how pavements are maintained (i.e., not all pavements are allowed to reach terminal serviceability). Also implicit in this change in terminology is that a given pavement can be described using a string of information that represents an optimal treatment sequence and timing.

To demonstrate the differences, the remaining life information for each of the 338 pavement sections used in the optimization was obtained from MDSHA data and compared to the timing until first treatment from the RSI optimization. In this case, the first 40 years of the 60-year analysis was used because a portion of sites had no work recommended in the first 20 years of the 40-year analysis. Pavements with no work recommended in the first 20 years of the 40-year analysis were generally newer pavements on routes that have low rates of deterioration and relatively high condition thresholds. For example, nine pavements in relatively good initial condition (IRI < 100 inches/mi, FCI > 80, and SCI > 85) in functional class 6 (IRI threshold of 250 inches/mi, FCI threshold of 30, and SCI threshold of 45) had no work recommended in the first 20 years of the 40-year analysis. Incidentally, many of these pavements had preservation recommended within the first 40 years of the 60-year analysis.

Any pavements with no treatment recommended in the first 40 years were placed in the 45-year bin. The results are shown in figure 61, and it can be seen that the optimal decision generally results in the first treatment being placed before the remaining life is reached on average. It should be noted that the RSL computes the time until the pavement reaches a predefined terminal condition, while RSI computes the time until any treatment is applied. In addition, figure 62 demonstrates that practically no relationship exists between the time until the first pavement treatment from the RSI optimization and the remaining life information obtained from MDSHA.

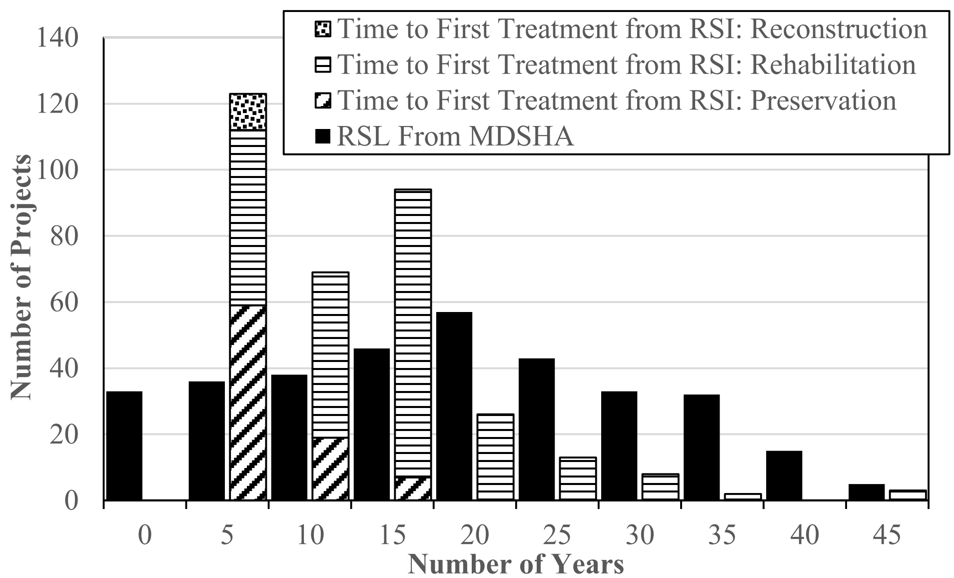


Figure 61. Graph. Remaining life (MDSHA) compared to time until first treatment from RSI.

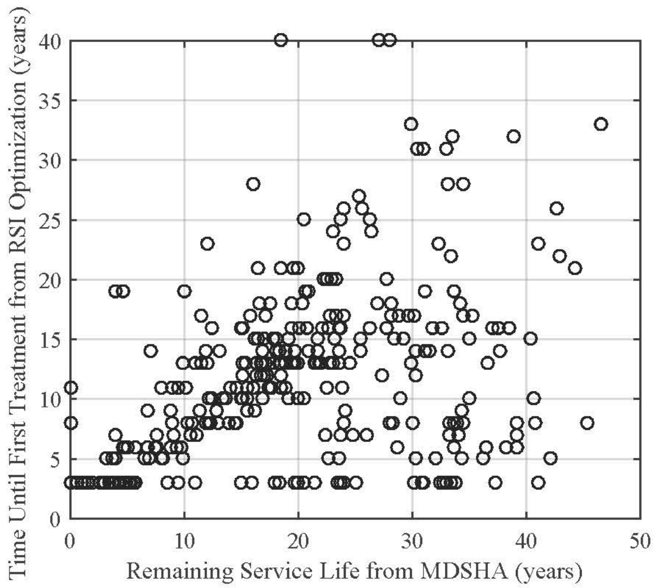


Figure 62. Graph. Time until first treatment from RSI as a function of remaining life.

More fundamentally, RSI defines specific intervals until certain M&R activities should be performed on a pavement. As demonstrated throughout this chapter, the intervals can be developed using optimization based on minimizing lifecycle costs. To demonstrate how the final RSI intervals look after the optimization, a sample of segments are demonstrated in table 19. The RSI columns in table 19 contain the number of years relative to 2014 that the actions should be undertaken.

Table 19. Example of RSI implemented on MDSHA pavement sections.

Pavement Section ID	Pavement Section Length (lane-miles)	RSI Preservation (year)	RSI Rehabilitation (year)	RSI Reconstruction (year)	NPV of 20-Year M&R Costs ($)
1039	2.82	7, 19			194,200
1133	1.34	15	3		517,330
1620	7.66	10, 17		3	6,035,700
3138	3.67	10, 17	3		1,268,900

Blank cell = Treatment type not needed.

Discussion

Validating the RSI using the MDSHA models successfully demonstrated that the RSI concept can be implemented at a State transportation department with minimal changes to the condition metrics, performance models, and other information. However, implementing the RSI requires a long-term outlook for the treatment selection process in order for the optimization to provide adequate information. For example, implementing the objective function presented in figure 40 (minimizing costs subject to condition thresholds) in MDSHA's typical 6-year outlook would result in the majority of pavement sections requiring no maintenance and would also lead to the eventual long-term decline in network condition. Instead, it was demonstrated that the time horizon for the analysis should be based on the deterioration characteristics of the pavement (e.g., rate of deterioration) and should also be based on the characteristics of the objective function in the optimization.

Although the validation effort presented in this chapter resulted in several insights into pavement management practices, it is important to recognize several key differences in the two procedures that were compared. The differences are summarized in table 20.

Table 20. Key differences in the MDSHA and RSI methodologies.

Parameter	MDSHA	LCCA-based RSI methodology
Analysis period (years)	6—uses the results from the third and fourth years for project scheduling. (First and second year were previously scheduled.)	40—used in the analysis presented in this section but can be varied.
Minimum years between treatment	Yes.	No—not used in the analysis presented in this section. However, the treatment constraints sometimes dictated a minimum age of the pavement before a treatment was considered.
Treatment constraints (e.g., no preservation on poor pavement condition)	Yes.	Yes.
Objective function	• Identifies a single treatment that causes maximum performance extension and minimum cost for each pavement section. Also considers VMT and lane-miles. • Suggests treatment for each pavement with in the 6-year analysis period. • Provides a value that can be used in network-level prioritization for the segment obtained from the objective function (figure 37).	• Identifies sequence of treatment that minimize LCC for each pavement section (figure 40). • Selects treatment timing based on lowest LCC. • Develops recommendation based on unconstrained budget analysis. Budget-constrained network-level prioritization can be handled when the cost of delayed treatment is computed. VMT and lane miles can also be considered.

The objective function is a mathematical expression of the agencies' preferences and determines the results of the optimization. For example, the MDSHA objective function (figure 37) explicitly includes a measure of benefit in the numerator, and the results of the optimization indicated that it leads to a much more aggressive approach toward improving network condition than the lowest lifecycle agency cost objective function used in the RSI validation (figure 40). However, it is important to note that the MDSHA approach is not designed to select treatments over the 6-year time frame. Instead, the MDSHA approach is to evaluate a 6-year horizon but use the results from years 3 and 4 to select optimal strategies. In addition, there is no explicit measure of benefit in the objective function used for the RSI validation. Instead, the benefit in the RSI validation is implicit; if managing a network in good condition results in overall lower costs, then the network condition will improve over a long enough time horizon.

Although the results of optimization are almost entirely dependent on the objective function that is developed to express the goals of the analysis, the comparison of the MDSHA procedure and the RSI optimization approach yields many findings. In every case, the MDSHA procedure resulted in higher annual costs and better overall condition earlier in the time horizon. This tradeoff between M&R costs and condition is expected, and the differences between the MDSHA and RSI approaches are a result of the differences in the objective functions used to perform the optimization.

MDSHA has developed models to account for the improvement in condition due to a treatment as a function of the initial treatment condition. The RSI formulation developed for this project would not have been possible without the use of the MDSHA models, business rules, condition data, and cost data. For example, rehabilitating a pavement with a lower IRI results in a smoother pavement than rehabilitating a pavement with a higher IRI (though the same does not hold true for the FCI and SCI) using the MDSHA models. In addition, several performance models were related to the last treatment applied (e.g., the pavement roughness grew at a slower rate after the application of micro-surfacing), and several costs were a function of the pavement condition. These relationships had a direct impact on the optimal treatment schedules developed during the optimization and led to preservation being recommended when the pavement was in a better condition. Absent these models (i.e., if the effect of a treatment (posttreatment performance) did not depend on the pretreatment condition), more preservation would be recommended later in the pavement life simply because of the costs being discounted over time.

Finally, the optimization algorithm used in this validation is computationally intensive; the resources required to converge on a solution are relatively high. However, the algorithm was not designed to balance efficiency with robustness. Instead, the algorithm was designed to increase certainty of converging on the global optimum, as opposed to a local optimum. In addition, the use of cloud computing resulted in the ability to develop solutions for a relatively large number of pavements over a relatively short time. Additional work on the algorithm, such as better balancing the population size as the algorithm progresses or developing better methods to intelligently add diversity to the population, would undoubtedly reduce computational intensity.

It is clear that the following enhancements to MDSHA would make an already mature process even more efficient:

- Posttreatment improvement in pavement condition and performance are affected by the pretreatment pavement condition. Rehabilitation on pavements in better condition will yield better posttreatment condition than on pavements in poor condition. However, when rehabilitation treatment is applied, the FCI and SCI models currently reset to 100 percent irrespective of pretreatment condition, and these models should be improved.

- Performance prediction is typically based on the previous applied treatments and conditions. These factors can be used in improving the performance predictions instead of using only the age of the current treatment (see figure 34 through figure 36). The use of only treatment age will predefine the treatment performance irrespective of the pavement condition at the treatment time.

- The last treatment is used to predict future IRI performance, but the efficiency of the preservation treatments is dependent on the past rehab treatments that still provide a structural component to the pavement structure. A structural evaluation parameter is needed to account for overall pavement condition instead of considering only the last treatment.

Conclusions

The following conclusions were developed based on the analysis and results presented in this chapter:

- The implementation of the RSI approach can be accomplished with relatively few changes to agency models and data. In this validation effort, only the optimization method used in the treatment selection was modified, given the state of the models provided by MDSHA. Although this is a significant change from the perspective of network-level decision processes, no changes to data collection, performance models, or treatment selection criteria were attempted.

- In any decision analysis framework, agency goals are mapped to the decisionmaking process through the construct of the objective function. Consequently, the objective function and underlying assumptions used in the analysis have a significant impact on the long-term condition and projected yearly costs of the pavement network. Therefore, many key decisions, such as the analysis period, should be reflective of the objective function used in the analysis.

- In addition to being influenced by the objective function, the analysis period should be based on the performance characteristics of the pavement condition if minimization of costs is a goal in the optimization. For example, if a network of pavements generally deteriorates at a relatively lower rate, the time horizon should be much longer than a network of pavements that deteriorates at a higher rate. This is because the analysis period should cover enough time for multiple treatments to be required for given pavement sections.

- If the construct of the objective function is to minimize costs subject to condition thresholds, then a significant portion of time at the end of the analysis period should be neglected when the end of analysis period remaining value is not considered. This is because the optimal solution will generally be to maintain a pavement in good condition until such a time that, when do-nothing is selected for the remainder of the pavement life, the pavement does not require maintenance. For example, if a 40-year analysis period is selected and it takes 20 years for a good pavement to reach the condition thresholds, the optimal solution will be to maintain the pavement in good condition for the first 20 to 25 years and then allow it to deteriorate toward the thresholds.

- Although the optimization algorithm presented in this report is computationally intensive, parallel computing using cloud resources provides an economical means for addressing large network optimization issues. Computational resources should no longer be viewed as a constraint in optimization.

Recommendations

The following general recommendations are based on the results of this validation process:

- The RSI concept should be pursued and implemented by agencies in an effort to enhance their decision processes as well as improve how M&R needs for pavements are effectively communicated to stakeholders at all levels.

- More research is needed to better understand the tradeoff between computational intensity and solution robustness when using genetic algorithms to perform optimization specific to pavements. This research may help decrease the computational resources required for using the genetic algorithm as a strategy selection technique over long-term horizons.

- Hard constraints were used for the optimization in this chapter. Essentially, if the condition fell below a specified value, then the costs were severely penalized. However, more optimal solutions may be found if these constraints are softened, which can be done using a goal programming type of approach. Future optimization procedures that maintain a focus on minimizing costs subject to condition thresholds should consider evaluating the use of these soft constraints instead of the use of hard constraints.

CHAPTER 6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The RSI concept was developed to provide an alternative to the long-standing and confusing RSL terminology. The RSI concept does not provide an alternative to assessing the health of the network or making decisions about how to spend available funds. It simply provides a clear terminology and a logical process that will create a consistent construction event-based terminology and understanding (i.e., types of construction events and the timing of those events within the concept of LCC and/or other prioritization approaches based on streams of future construction events). An added benefit of adopting the RSI terminology is that the methodology provides a readily available way to communicate impacts of alternate budget scenarios. The RSI concept considers the complete M&R activity of the pavement system and does not simply consider the end of life as promulgated by the RSL philosophy.

While threshold values can be used to determine the time until future construction events are needed, in the original formulation of RSI, LCC optimization was recommended to determine when preservation, rehabilitation, and reconstruction are needed. During this project, an LCC algorithm was developed that finds the optimum time for treatment subject to threshold constraints based on meeting minimum LOS. This algorithm was used during the validation effort based on the MDSHA network.

Reconstruction is one cost (with the caveat that the user costs are not included), and the resulting condition is the same (new) no matter the pretreatment condition, unlike preservation and rehabilitation treatment. The threshold for reconstruction can be considered the minimum LOS and structural condition when lower-level treatments are no longer cost effective. At this time, the RSI for any treatment should remain zero, essentially reflecting that treatment is needed. This is different than RSI numerics for preservation and rehabilitation because once either of these values reach zero, non-zero values of RSI should still exist for at least one other treatment category. As the condition of the pavement continues to deteriorate beyond the minimum LOS, the RSI remains zero, signaling that treatment is still needed. As a way to improve communication of this need, the years past due can also be used in conjunction with an RSI of zero. For instance, take two pavement sections that have both exceed the reconstruction thresholds; one section has just exceeded the threshold this year, and the other section exceeded the threshold 2 years ago. Both pavement sections have an RSI of zero for all treatments, but the second pavement section could be said to be past due by 2 years. An agency should not have many pavements with an entire string of zeros representing the RSI, and therefore, each of the cases should be treated individually as needed.

As the RSI concept evolved to represent a more ideal system based on optimizing the treatment selection considering all possible treatments and treatment timings instead of being threshold driven, it is no longer an issue to consider more than one type of construction trigger. The evolution from a change in terminology to a change in approach resulted in all construction triggers (i.e., preservation, rehabilitation, or reconstruction) and minimum LOS being considered in selecting the optimum treatments. The resulting RSI numerics represent the optimum and do not focus on one type of construction trigger.

Summary Observations from Project-Level Analyses

The following observations sumarize the most important findings and conclusions from the RSI concept validation effort performed at the project level presented in chapter 4:

- Regular pavement structural evaluation provides the opportunity to identify the optimum treatment sequence that yields the LLCC for a given pavement section.

- Use of surface cracking as a structural indicator limits the PMS to potentially reactive treatment options because it is a lagging indicator of level of structural deterioration below the pavement surface and therefore may not lead to selection of the LLCC option.

- Tensile strains can be a leading indicator to identify pavement structural deterioration before surface cracks appear. Depending on road classification, threshold tensile strains can be used to select optimal treatment and maintain the pavement in a state of good repair.

- At the network level, tensile strains are a better parameter to evaluate and track pavement structural condition. A simple and robust correlation between strains and deflection parameters can be used along with performance models to evaluate and predict future performance. For example, the same fatigue damage model used in pavement design can be used in pavement management when tensile strains are estimated from SCI, as demonstrated in this study.

- Treatment sequences evaluated using LCCA should yield pavement in a state of good repair at the end of the analysis period. Longer analysis periods should be used in the LCCA. With a shorter analysis period (such as 6 years), the LCCA could yield preservation treatments (such as resurfacing), which would satisfy the minimum LOS but lead to pavements in poor structural condition at the end of the analysis period.

- The asset value of each pavement section at the start and end of the analysis period is required for a comprehensive LCCA at the network level. The need for asset value can be substituted by an approach in which, at the end of the analysis period, the chosen optimum treatment sequence yields tensile strains that are similar to other, costlier alternatives.

Summary Observations from Network-Level Analyses

The following observations sumarize the most important findings and conclusions from the RSI concept validation effort performed at the network level presented in chapter 5:

- As part of the network-level RSI validation effort, optimal strategies (based on LLCC) were developed for a pavement network. It was found that the RSL was not related to the time until each pavement should be scheduled for work (from the optimization). In other words, the RSL may provide an indication of the current network condition, but it bears no relationship to the future maintenance needs of the pavement.

- The analysis in chapter 5 compared two objective functions, each of which was directly linked to specific objectives. In any decision analysis framework, agency goals are mapped to the decisionmaking process through the construct of the objective function. Consequently, the objective function and underlying assumptions used in the analysis have a significant impact on the long-term condition and projected yearly costs of the pavement network. Therefore, many key decisions, such as the chosen analysis period, should be reflective of the objective function used in the analysis.

- The analysis period that an agency uses to analyze lifecycle costs should be directly linked to the objective function defined by an agency. The objective function that was used for the RSI validation (defined in chapter 5) was to minimize lifecycle maintenance costs for the pavement network while also ensuring that no pavement fell below a specified threshold condition. In this case, it was found that the time horizon for the LCCA needed to be approximately 20 years longer than the desired analysis period.

CONCLUSIONS

The results from the validation efforts presented in this report support the conclusion that the RSI represents a valid approach to determining and communicating future M&R needs of a pavement instead of defining pavement life using a single number. The results in chapter 5 showed that the remaining life is essentially not related to the time until the next pavement treatment in an optimal strategy. In addition, developing optimal strategies for pavement management at the project level (chapter 4) and network level (chapter 5) represents enhanced approaches to planning pavement M&R needs.

Based on the validation results from chapters 4 and 5, it can be concluded that optimal pavement management decisions should not be predicated on condition-based threshold values for treatments. Instead, optimal pavement management strategies may include the application of treatments well before a threshold condition is reached. Therefore, an important step toward the implementation of the RSI is the development of a procedure to determine optimal strategies for pavement M&R scheduling.

RECOMMENDATIONS

As a result of the validation and application of the RSI concept efforts at the project, network, and strategic levels, the following recommendations are provided:

- Improvements to HPMS 2010+ data for data consistency and completeness for strategic level inputs are needed.

- Evaluation of simplified MEPDG models used in the PHT analysis tool is required to determine the cause of erroneous predictions and should consider both models and input data.(24)

- Asset valuation is a critical input to LCCA, as demonstrated in chapter 4. The asset value cannot be obtained from the last treatment applied to the section. A comprehensive method that accounts for the pavement system as a whole should be developed.

- Use of TSDDs in structural evaluations should be explored. They can be used to overcome limitations of using FWD testing at the network level.

- Chapter 4 showed the merit of using tensile strain as a robust pavement structural condition indicator and for identifying optimum treatment sequences. It was shown that a pavement is optimally maintained when the tensile strain is within certain range. Further research is needed in identifying the optimum tensile strain range that typically changes with pavement classification.

- As part of implementing the RSI at agency levels, agencies should reevaluate their approach to treatment selection and strategy optimization to ensure that the objective function used in the analysis adequately captures agency goals.

- Additional research regarding modern network-level optimization techniques should be conducted in an effort to move agencies away from threshold-driven decisionmaking. The continuous growth of computational resources has brought optimization techniques that used to be too computationally intensive into the realm of implementability.

- Agencies should enhance their performance prediction models to demonstrate the relationship between the effectiveness of an M&R treatment and the condition of the pavement just prior to treatment. These models would provide critical information required for making more optimal decisions at the network level.

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