Validation of Pavement Performance Measures Using LTPP Data: Final Report

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Research, Development, and Technology
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LTPP™

FOREWORD

This report documents a study undertaken to validate the proposed pavement performance measures identified in the Federal Highway Administration (FHWA) Notice of Proposed Rulemaking (NPRM) issued in response to the Moving Ahead for Progress in the 21st Century Act, which included requirements pertaining to transportation performance management.[1,2] To accomplish this objective, three major activities were carried out: (1) a literature review that yielded criteria for evaluation of the proposed performance measures and translation of distress data from the Long-Term Pavement Performance database to the pavement condition metrics used by the performance measures proposed in the NPRM; (2) a review and validation of performance measures over time, both within and between construction events, and against the thresholds identifying performance; and (3) an analysis of alternate pavement condition threshold values, the change in the metrics and overall pavement conditions over time, and the metrics driving the overall condition and performance.

The findings presented in this report suggest that the performance measures established by the NPRM and ultimately required by the issuance of the Final Rule by FHWA are appropriate because all the metrics have an effect on overall condition and performance measures.

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16. Abstract
Federal Highway Administration (FHWA) issued a Notice of Proposed Rulemaking to establish performance measures for the Interstate Highway System (IHS) and the National Highway System (NHS) to assess the condition of the pavement on the IHS and NHS.[1] The performance measures, as proposed by FHWA, to assess the condition of the pavement are based on the percentage of pavements on both the IHS and NHS (excluding the IHS) in good and poor condition. The condition of the pavements is to be determined based on the following metrics: International Roughness Index, cracking percent, rutting, and faulting. The overall objective of the study was to validate the proposed pavement performance measures and demonstrate their use within asset management. Performance and distress data from the Long-Term Pavement Performance database were translated into the pavement condition metrics used by the performance measure proposed by FHWA. The performance measure validation considered review of the performance measures over time to determine if they followed a logical trend; comparison of performance measures against maintenance and rehabilitation (M&R) activities to demonstrate if the performance measures are impacted by M&R activities; and review of the performance measures against thresholds for logic and reproducibility, temporal analysis, effects of alternate thresholds, and identification of performance measure drivers. Standalone guidelines for informing decisionmaking to affect pavement performance measures were also developed based on the study findings; they are provided in a companion report.

17. Key Words
MAP-21, FAST Act, Long-Term Pavement Performance, LTPP, pavement performance measures, pavement metrics, pavement condition, IRI, cracking, rutting, faulting

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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

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ANOVA	analysis of variance
CRCP	continuously reinforced concrete pavement
DOT	Department of Transportation
FHWA	Federal Highway Administration
HPMS	Highway Performance Monitoring System
IHS	Interstate Highway System
IRI	International Roughness Index
JPCC	jointed portland cement concrete
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
LTPP	Long-Term Pavement Performance
M&R	maintenance and rehabilitation
MAP-21	Moving Ahead for Progress in the 21st Century Act
NHPP	National Highway Performance Program
NHS	National Highway System
NPRM	Notice of Proposed Rulemaking
PMS	pavement management system
PPDB	Pavement Performance Database
PSR	Present Serviceability Rating
SDR	Standard Data Release
SMP	Seasonal Monitoring Program
TRB	Transportation Research Board

CHAPTER 1. INTRODUCTION

BACKGROUND

The Moving Ahead for Progress in the 21st Century Act (MAP-21) legislation required performance measures to be established for the Interstate Highway System (IHS).[2] It also required that State departments of transportation (DOTs) develop and implement a risk- and performance-based Transportation Asset Management Plan covering the pavements and bridges within the National Highway System (NHS), as a minimum. Subsequently, in January 2015, the Federal Highway Administration (FHWA) issued a Notice of Proposed Rulemaking (NPRM) to establish performance measures to assess the condition of the pavements on the NHS and IHS.[1]

In January 2017, FHWA issued the Final Rule (effective February 17, 2017) to implement the performance management requirements of MAP-21 and the Fixing America's Surface Transportation Act.[3] The four pavement performance measures to assess pavement condition established by the NPRM and confirmed by the Final Rule are as follows:[4]

- Percentage of pavements on the IHS in good condition.
- Percentage of pavements on the IHS in poor condition.
- Percentage of pavements on the NHS (excluding the IHS) in good condition.
- Percentage of pavements on the NHS (excluding the IHS) in poor condition.

The condition of the pavements is to be determined based on the following metrics:[4]

- International Roughness Index (IRI).
- Cracking percent.
- Rutting.
- Faulting.

The pavement condition rating thresholds are provided in table 1.[4]

The overall condition of the pavement is determined based on the individual metric conditions as follows:

- For asphalt and jointed concrete pavements, the pavement is classified as good condition if all three metrics are in good condition. The pavement is classified as poor condition if two or more of the metrics are in poor condition. All other combinations of metric conditions classify a pavement as fair.[4]

Table 1. Pavement condition rating thresholds.

Condition Metric	Performance Level	Threshold
IRI	Good	<95
IRI	Fair	95–170
IRI	Poor	>170
Percent cracking, AC	Good	<5%
Percent cracking, AC	Fair	5–20%
Percent cracking, AC	Poor	>20%
Percent cracking, CRCP	Good	<5%
Percent cracking, CRCP	Fair	5–10%
Percent cracking, CRCP	Poor	>10%
Percent cracking, JPCC	Good	<5%
Percent cracking, JPCC	Fair	5–15%
Percent cracking, JPCC	Poor	>15%
Rutting	Good	<0.20
Rutting	Fair	0.20–0.40
Rutting	Poor	>0.40
Faulting	Good	<0.10
Faulting	Fair	0.10–0.15
Faulting	Poor	>0.15

AC = asphalt concrete; CRCP = continuously reinforced concrete pavement;
JPCC = jointed portland cement concrete.

- For CRCPs, if both metrics are in good condition, the pavement is classified as good. The pavement is classified as poor if both metrics are in poor condition. All other combinations of metric conditions classify the pavement as fair.(4)

The Final Rule allows State DOTs to report Present Serviceability Rating (PSR) instead of metrics where the speed limit is under 40 mph.(4) The pavement condition rating thresholds when using the PSR metric for all pavement types are provided in table 2.(4)

Table 2. Pavement condition rating thresholds using PSR metric.

Rating	Metric Range
Good	≥4.0
Fair	>2.0 and <4.0
Poor	≤2.0

Three of the four pavement condition metrics are used to determine the overall condition for AC and JPCC Highway Performance Monitoring System (HPMS) pavement sections, while only two pavement condition metrics are used to determine the overall condition for CRCP. The Final Rule notes that each of the pavement condition metrics are to be collected on the full extent of the IHS in the rightmost travel lane in the inventory direction of mainline travel on an annual basis.(4) For the non-interstate NHS pavements, data are to be collected for the full extent of the rightmost lane in one direction of travel on a biennial frequency.(4) Percent cracking, rutting, and faulting are not required to be collected on the non-interstate NHS until the 2020–2021 data collection cycles.[4]

For State DOTs to be comfortable with the stated performance measures and therefore to aid in their implementation, it was felt that an important first step was to demonstrate that these measures are effective—a valid performance measure is a true measure of condition, follows a predictable trend over time, and is repeatable, reproducible, and understandable by those who use it.[5] Illustrating that the performance measures are measurable and adequately respond to repair strategies would also assist State DOTs in having confidence with the measures. Moreover, a thorough review of the performance measures would assist FHWA in identifying weaknesses in the measures and methods for improving on the measures selected.

Due to the completeness and volume of data contained in its Pavement Performance Database (PPDB), the Long-Term Pavement Performance (LTPP) program was poised to assist in implementation of the performance measures—both in the validation of the performance measures as well as in the development of guidelines to show agencies what metrics drive the performance measures and impacts of various construction treatments on the proposed performance measures.

PROJECT OBJECTIVES, TASKS, AND OUTCOMES

The objectives of the research study presented in this report were to validate the pavement performance measures and to demonstrate their use within the pavement decisionmaking process. To accomplish these objectives, the following tasks were undertaken by the project team:

1. Kickoff meeting.
2. Literature review and LTPP distress data translation.
3. Review and validation of performance measures: time, treatment, and threshold impacts.
4. Interim report.
5. Performance modeling: thresholds, temporal changes, and drivers.
6. Development of guidelines for informing decisionmaking to affect pavement performance measures.
7. Final report.

At the start of the research effort, a kickoff meeting was held to clearly define the project approach, deliverables, and schedule. Next, under task 2, a literature review was conducted to identify criteria to use in the evaluation of the performance measures. Concurrently, as part of the same task, distress data from the LTPP PPDB were translated to the pavement condition metrics used by the performance measure. Once translated, the criteria for review of the performance measures were established, and the data were reviewed in accordance with these criteria. The review conducted under task 3 included the following:

- Review of the performance measures over time to determine if they followed a logical trend.
- Comparison of performance measures against maintenance and rehabilitation (M&R) activities to demonstrate if the performance measures are impacted by M&R activities.
- Review of the performance measures against thresholds for logic and reproducibility.

The data review was also intended to identify the trends and to gain an understanding of the strengths and weaknesses associated with the performance measures. The tasks 2 and 3 approach and findings were documented in the task 4 interim report.

In light of the positive results from the initial effort, which showed the performance measures met the established effectiveness criteria, the following additional analyses were conducted under task 5:

- Threshold analysis to consider alternate pavement condition threshold values.
- Temporal analysis of IHS LTPP test sections to investigate the rate of change in the metrics and overall pavement conditions over time.
- Review of performance driver measures to determine metrics driving the overall condition and performance for both fair and poor conditions.

In performing these additional analyses, the pavement metric thresholds that would eventually be included in the Final Rule were used—they were provided to the project team by FHWA. The analyses conducted under task 3 made use of the pavement metric thresholds contained in the NPRM. The differences in and impacts of the two sets of thresholds are addressed in the report.

Based on the outcomes from the tasks 3 and 5 analyses, guidelines were prepared under task 6 to provide information and direction to highway agencies on key pavement decisionmaking issues, including an understanding of the drivers affecting the performance measures as well as the effects of M&R treatments on the metrics and overall condition. The goal of these guidelines, which are provided in a companion report, is to illustrate to agencies a potential method to move the overall condition from poor to fair to good.(6)

Ultimately, the entire research effort—including the approach, findings, conclusions, and recommendations—was documented in this final report.

REPORT ORGANIZATION

The chapters included in the report, along with a brief description of their contents, are summarized as follows:

1. Introduction: Provides the project background, objectives, tasks, and outcomes. It also describes the organization of the report.

2. Literature Review: Presents the results of the literature review that yielded the criteria for evaluation of the proposed performance measures.

3. Distress Data Translation: Summarizes the translation of distress data from the LTPP PPDB to the pavement condition metrics used by the performance measures and development of the project database consisting of pavement condition metrics, performance measures, and other relevant data based on the LTPP PPDB.

4. Temporal, Treatment, and Threshold Impacts on Performance Measures: Details the results from the review of the pavement metrics and performance measures over time, both within and between construction events (i.e., referring to a change in pavement structure). In addition, it presents the results of the review of the performance measures against the thresholds identifying performance.

5. Other Performance Measure Considerations—Thresholds, Temporal Changes, and Drivers: Details the results from the analysis of the alternate pavement condition threshold values, the change in the metrics and overall pavement conditions over time, and the metrics driving the overall condition and performance.

6. Development of Guidelines for Informing Decisionmaking to Affect Pavement Performance Measures: Summarizes the development of the guidelines intended to provide information to highway agencies on key pavement decisionmaking issues, with a focus on potential strategies to move the overall condition from poor to fair to good.

7. Summary, Conclusions, and Recommendations: Summarizes the findings as a result of the review and validation of pavement performance measures conducted throughout the entire research effort.

In addition to the above seven chapters, references cited throughout the report are listed at the end of the report. Standalone guidelines for informing decisionmaking to affect pavement performance measures were also developed based on the study findings; they are provided in a companion report.[6]

CHAPTER 2. LITERATURE REVIEW

The objective of the literature review detailed in this chapter was to identify criteria to be used in reviewing and assessing the NPRM pavement performance measures. The literature review begins with the NPRM evaluation criteria followed by other potential criteria found in literature and concludes with the recommended criteria and performs an initial assessment of the NPRM measures.

NPRM EVALUATION CRITERIA

In the NPRM, FHWA proposed that the performance measures used to assess pavement condition be based on data within HPMS—including IRI, cracking percent, rutting for asphalt pavement, and faulting for jointed concrete pavements—as well as the following criteria:(1)

- Consider more than roughness.
- Utilize pavement condition attributes currently reported at a national level.
- Utilize pavement condition attributes where data collection and reporting standards exist today.
- Result in an assessment approach that is consistent with typical conceptual approaches used today by State DOTs to assess condition.
- Consider an approach that can be implemented so that State DOTs can establish targets within a 12-mo period after FHWA establishes the performance measures without introducing a considerable burden on State DOTs.

In addition, as stated in the NPRM, FHWA used the following criteria to assess the proposed measures for national use and readiness for implementation accurately and reliably to carry out the National Highway Performance Program (NHPP):(1)

- Is the measure focused on comprehensive performance outcomes?
- Has the measure been developed in partnership with key stakeholders?
- Is the measure maintainable to accommodate changes?
- Can the measure be used to support investment decisions, policymaking, and target establishment?
- Can the measure be used to analyze performance trends?
- Have the feasibility and practicality to collect, store, and report data in support of the measure been considered?
- Is the measure timely?

- Is the measure consistent?
- Is the measure complete?
- Is the measure accurate?
- Is the measure accessible?
- Are the data integrated?

The above criteria provide a comprehensive list of issues that could be investigated in an assessment of the performance measures. For this project, the criteria provided the foundation for establishing criteria for review that were modified to meet the specific project objectives. For example, the criteria of being developed in partnership with key stakeholders; being able to accommodate changes; being used to support investment decisions, policymaking, and target establishment; and feasibility and practicality to collect, store, and report data in support of the measures were not within the scope of this project, and therefore these criteria were not considered further.

In addition to the stated criteria, FHWA conducted a series of studies under the Improving FHWA's Ability to Assess Highway Infrastructure Health effort.(5,7–9) The pilot study under this effort resulted in the following conclusions relevant to the performance measures issued within the NPRM:(7)

- The level of confidence associated with the various pavement condition measures evaluated within the context of good, fair, poor is summarized below:
    - There is a high level of confidence with IRI given the acceptable correlation found in the study between the HPMS, State DOT pavement management systems (PMS), and field data sources.
    - A medium level of confidence exists for the rut depth data, and additional investigation is required to resolve the bias issue between the HPMS or State DOT PMS data and the field data.
    - For the remaining condition measures (cracking percentage, cracking length, and faulting), additional work is required to standardize data collection and processing at the national level.
- Because of the high level of confidence, pavement roughness in terms of IRI is feasible and the recommended measure for use as the American Association of State Highway and Transportation Officials (AASHTO) tier 1 good, fair, poor indicator. When used, the indicator should specifically mention this is a ride quality condition, not a pavement condition.
- Because IRI does not provide a complete picture of pavement condition, other measures were considered in addition to or in combination with IRI, including selected distresses, structural capacity, and remaining service life. However, given the level of confidence

associated with these other pavement condition measures, significant work is required before they can be implemented.

- Given the need for consistent, high-quality data at the national level, use of the HPMS dataset to drive the good, fair, poor indicator and possible associated flags is considered the best option at present and in the near future. However, this does not imply that improvements to the HPMS data are not possible and/or required. Using State DOT PMS data does not seem feasible at this time due to the differences between States. Collecting field data on the entire interstate system likewise does not appear economically justified at this time.

A followup to the pilot study was undertaken to develop a next-generation pavement performance measure that provided an accurate and repeatable assessment of functional condition.(8) The measure was to combine IRI, cracking, and rutting or faulting into a composite index. In addition, this measure was to rely solely on HPMS data. However, because each individual distress was considered to provide a different diagnosis of the pavement's condition, the focus in the study shifted away from a single composite index to using the distresses individually. Consequently, the study focused on development of recommendations for data collection, processing, and quality control/quality assurance for the individual distresses, which yielded the following recommendations for future research to improve current capabilities in data collection and processing:(8)

- Additional research is required to ascertain a better understanding of the impact of changes in curling on faulting measurements.

- Additional research is needed to improve the overall faulting measurement. In particular, the detection of joints and cracks that have little to no faulting within the longitudinal profile data using automated methods is nearly impossible. Potentially, the longitudinal profile data could be married to the cracking imagery to assist in identifying the cracks and joints within each segment.

- Additional research needs to be undertaken to review the threshold levels associated with evaluating condition based on faulting. The field validation identified that the threshold values are probably too strict, but based on the results of that effort, definitive levels could not be identified.

- Additional work is required to review the threshold levels associated with evaluating condition based on cracking. The field validation efforts related to cracking were inconclusive due to the difficulty of rating the distress and the general lack of cracking on the pavement reviewed.

- Additional consideration needs to be given to sealed cracks and length of ruts. These items are not currently considered by the HPMS guidelines.

OTHER POTENTIAL EVALUATION CRITERIA

The remainder of this literature review focused on identifying references to help finalize the list of criteria to be used in the project. Many of the review criteria and characteristics of good performance measures translate across many fields and are similar in nature. Industries outside of pavements use performance measures specific to their field, and many of the good characteristics of performance measures are appropriate to other applications.

Keebler et al. provide the following characteristics for assessing the best performance measures:(10)

- Is quantitative—the measure can be expressed as an objective value.
- Is easy to understand—the measure conveys at a glance what it is measuring.
- Encourages appropriate behavior—the measure is balanced to reward productive behavior and discourage game playing.
- Is visible—the effects of the measure are readily apparent to all involved in the process of being measured.
- Is defined and mutually understood—the measure has been defined by and/or agreed to by all key process participants.
- Encompasses both outputs and inputs—the measure integrates factors from all aspects of the process measured.
- Measures only what is important—the measure focuses on a key performance indicator that is of real value to managing the process.
- Is multidimensional—the measure is properly balanced between utilization, productivity, and performance and shows the tradeoffs.
- Uses economies of effort—the benefits of the measure outweigh the costs of collection.

According to the U.S. Army Corps of Engineers, characteristics of a good performance measure include the following:(11)

- Meaningful—significant and directly related to the mission and goal.
- Responsibility linked—matched to an organizational unit responsible for achieving the measure.
- Organizationally acceptable—valued by those within the organization.
- Customer focused—reflect the point of view of the customers and stakeholders.
- Comprehensive—include all key aspects of performance.

- Balanced—include several types of measures (i.e., outcome, efficiency, and quality measures).

- Timely—use and report data in a reasonable timeframe.

- Credible—based on accurate and reliable data.

- Cost effective—based on acceptable data collection and processing costs.

- Compatible—integrated with existing financial and operational systems.

- Comparable—useful for making comparisons with other data over time.

- Simple—easy to calculate and interpret.

A report issued by the Transportation Research Board (TRB) provided the following criteria to measure effectiveness of a performance measure:(12)

- Is meaningful.
- Describes how well the goals and objectives are being met.
- Is simple, understandable, logical, and repeatable.
- Shows a trend.
- Is unambiguously defined.
- Allows for economical data collection.
- Is timely and sensitive.

The next sources are specific to pavements. According to Shahin and Kohn, a pavement performance measure should meet the following criteria:(13)

- Standard calculation methodology.
- Standard collection methodology.
- Reproducible.
- Expedient.
- Useful for identifying needs.
- Easily understood.
- Minimal training time.

Based on Corley-Lay, a good performance measure for pavement should do the following:(14)

- Be economical to measure.
- Address both functional and structural performance.
- Be relevant to both concrete and asphalt.

RECOMMENDED EVALUATION CRITERIA

The information gathered from the literature review was used to establish the evaluation criteria to perform the review and assessment of the performance measures as proposed in the NPRM.

These final recommended evaluation criteria are presented in table 3. The criteria resulted from modifying the criteria used by FHWA to assess the proposed measures for national use and readiness for implementation accurately and reliably to carry out the NHPP. While derived from the NHPP criteria, many of the individual criterion were often included in the other references reviewed as part of the project. For example, “economical to measure” was directly or indirectly referenced in U.S. Army Corps of Engineers, TRB, and Corley-Lay, and “balanced” was referenced in Keebler et al., U.S. Army Corps of Engineers, and Corley-Lay.[10–12,14]

Table 3. Evaluation criteria and definitions.

Criteria	Definition
Comprehensive	Includes all key aspects of performance (i.e., addresses both functional and structural performance).
Balanced	Includes several types of metrics.
Able to show trends	Can be used to analyze performance over time.
Economical to measure	Does not increase burden on a State to collect/measure.
Appropriateness	Is suitable as a measure at the national level (including accuracy, timeliness, consistency, and precision).

The performance measures are comprehensive with respect to the state of the practice. That is to say, the state of the practice is not to include a network-level structural performance measure, but to instead use cracking as a surrogate for structural performance. The performance measures are balanced, as they comprise individual metrics for IRI, cracking, rutting, and faulting. The performance measures show the expected performance trend over time but are largely static, as will be demonstrated in the next two chapters.

Although attempts were made and approaches were considered to evaluate the performance measures against the remaining two criteria (economical to measure and appropriateness—including accuracy, precision, and timeliness), it was not possible to draw conclusions for these criteria based on the available data. The performance measures include metrics for IRI, cracking, rutting, and faulting. Although there may be some data available to determine the accuracy and precision of IRI and cracking, such data are not available for rutting or faulting. As such, it is not possible to evaluate the performance measures against these criteria. However, as will be shown in the temporal analyses presented later in this report, the pavement condition ratings have timeliness consistency. Moreover, evaluation of the performance measures for these remaining criteria were addressed under a separate study detailed in the FHWA Interstate Pavement Condition Sampling report.[15]

CHAPTER 3. DISTRESS DATA TRANSLATION

The LTPP PPDB is the world's largest and most complete database of pavement performance and supporting information. As such, the data contained in the LTPP PPDB provided an excellent opportunity for examining the pavement condition metrics and performance measures and how these metrics and measures perform over time with respect to a variety of factors such as pavement type, climate, and functional class. However, accomplishing this required the translation of pavement condition data contained in the LTPP PPDB to the pavement condition metrics and performance measures defined under the NPRM. The Final Rule was not issued until most of the project analyses had been completed; however, the pavement condition metrics and performance measures remained the same. Only the metric definitions for AC cracking, JPCC cracking, and various metric threshold values changed from the NPRM to the Final Rule. No revisions to computations were made based on the changes in the Final Rule.

The objective of this chapter is to detail the methods that were used for translating the LTPP pavement condition data to those data required to meet the project objectives. As stated in the introduction, both the NPRM and Final Rule make use of four pavement condition metrics to establish overall pavement condition and hence pavement performance measures. They are IRI, percent cracking, faulting, and rutting. Each metric, as defined by the NPRM (since the Final Rule was not available) and by LTPP as well as an alternate cracking methodology, is covered in this chapter.

PAVEMENT CONDITION METRICS

NPRM Pavement Condition Metrics

The pavement condition metric requirements, as published in the NPRM, were to be reported at an interval of 0.1 mi in accordance with the following requirements:

- IRI metric: IRI provides the roughness for each segment. Longitudinal profile data used for calculating the IRI for a segment were to be collected by a device meeting the requirements of AASHTO M328-14: *Standard Specification for Inertial Profiler*.[16] The data were to be collected in accordance with AASHTO R57-14: *Standard Practice for Operating Inertial Profiling Systems*.[17] The IRI was to be calculated in accordance with AASHTO R43-13: *Standard Practice for Quantifying Roughness of Pavements*.[18]

- Cracking metric: Cracking was to be computed in terms of a percent cracking metric. There are multiple definitions for percent cracking based on the surface type as summarized below. AC, JPCC, and CRCP refer to the surface layer of the pavement based on which survey was performed. For example, AC overlay of JPCC is considered AC pavement.

    - The percent cracking for AC pavements was reported as the percentage of the segment exhibiting visible cracking. Manual data were to be collected in accordance with AASHTO R55-10: *Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces*.[19] Automated data may have been collected in accordance with AASHTO PP67-14: *Standard Practice for Quantifying Cracks in*

Asphalt Pavement Surfaces From Collected Images Utilizing Automated Methods.[20] Percent cracking data were calculated as the percentage of the total area containing visible cracks to the nearest whole percent in each section. (Note: At the request of FHWA and as detailed later in this chapter, both total cracking as defined in the NPRM and cracking in wheel paths only as detailed in the Final Rule were considered in this study.)

  - Cracking data for JPCC were to be collected in accordance with the same standards for asphalt pavements as noted previously. Manual data were to be collected in accordance with AASHTO R55-10: *Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces*.[19] Automated data may have been collected in accordance with AASHTO PP67-14*: Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces From Collected Images Utilizing Automated Methods*.[20] Percent cracking was to be calculated as the percentage of slabs to the nearest whole percent within the sections that exhibit cracking.

  - Cracking data for CRCP were to be collected in accordance with the HPMS Field Manual.[21] The percent cracking was to be calculated as the percentage of pavement surface area with longitudinal cracking and/or punchouts, spalling, or other visible defects and reported to the nearest whole percent. Transverse cracking was not included in the computation.

- Rutting metric: Two options were offered within the NPRM for collection of rutting data. The first option was the collection of rut depth based on a five-point collection method in accordance with AASHTO R48-10*: Standard Practice for Determining Rut Depth in Pavements*.[22] The second option included the collection and processing of transverse profile data in accordance with AASHTO PP70-14: *Standard Practice for Collecting the Transverse Pavement Profile* and AASHTO PP69-14: *Standard Practice for Determining Pavement Deformation Parameters and Cross Slope From Collected Transverse Profile*, respectively.[23,24] The rut depth was computed as the average depth of rutting in inches to the nearest 0.05 inch for the segment.

- Faulting metric: All JPCC were required to have faulting collected in accordance with AASHTO R36-13: *Standard Practice for Evaluating Faulting of Concrete Pavements*.[25] The faulting was to be reported as the average height to the nearest 0.05 inch.

The Final Rule notes that each of the above pavement condition data metrics are to be collected on the full extent of the IHS in the rightmost travel lane in the inventory direction of mainline travel on an annual basis.[4] For the non-interstate NHS pavements, data are to be collected for the full extent of the rightmost lane in one direction of travel on a biennial frequency.[4] Percent cracking, rutting, and faulting are not required to be collected on the non-interstate NHS until the 2020–2021 data collection cycles.[4]

The pavement condition requirements in the Final Rule are consistent with the NPRM requirements, with one major exception—the percent cracking in AC pavements. In the NPRM, AC percent cracking was to be calculated as the percentage of the total area exhibiting longitudinal cracking (wheel path and non-wheel path), edge cracking, transverse cracking, fatigue cracking, and block cracking. In the Final Rule, the AC percent cracking was to be calculated as the percentage of the total area based on the area of the wheel paths exhibiting longitudinal cracking and fatigue cracking. As noted later in this chapter and at the request of FHWA, the percent cracking in AC pavements was calculated using both formulations in this project.

LTPP Pavement Condition Metrics

The relevant definitions for pavement condition data collected for the LTPP program are provided in this section. Data from the LTPP Standard Data Release (SDR) 28 (January 2014) were used to evaluate data needs and availability, while data from SDR 29 (July 2015) were used in the actual validation of the pavement performance measures.

- IRI metric: The LTPP program collects longitudinal profile data on each test section within the study. The IRI is calculated from the moving average data in accordance with ASTM E1926: *Standard Practice for Computing International Roughness Index From Longitudinal Profile Measurements*.(26) The ASTM standard is identified in AASHTO R43-13 as providing the means for calculating the IRI; therefore, the IRI contained in the LTPP database is calculated in the manner required by the NPRM.(18)

- For each section, multiple runs of data collection are performed at each visit, and an average of five runs per visit are stored within the LTPP PPDB. In SDR 28, the computed parameters data, including IRI in the left and right wheel paths, average of IRI in the wheel paths, and sometimes location between the wheel paths, were stored in the MON_PROFILE_MASTER table, which had a total of 133,364 records with an average of 11 visits or surveys per section and an average of 4 visits within a construction event. In SDR 29, these data were obtained from the MON_HSS_PROFILE_SECTION table, which had a total of 139,005 records.

- Cracking metric: The LTPP program collects cracking data in accordance with the LTPP Distress Identification Manual.(27) This data collection involves a detailed classification of the distress features on each section and includes mapping of the distress locations. While the LTPP distress maps are more detailed than that required under the NPRM, they permit translation of LTPP distress metrics to those used under the NPRM.

    - Data for AC pavements were obtained from the MON_DIS_AC_REV table, as only manual surveys were considered. In SDR 28, there were 11,855 manual surveys in the MON_DIS_AC_REV table with an average of 7 surveys per section and an average of 3 surveys per construction event.

    - Data for JPCC sections were obtained from the MON_DIS_JPCC_REV table, as only manual surveys were considered. In SDR 28, there were 4,926 manual surveys in the MON_DIS_JPCC_REV table with an average of 6 manual surveys per section and an average of 3 manual surveys per construction event.

- Data for CRCP sections were obtained from the MON_DIS_CRCP_REV table, as only manual surveys were considered. In SDR 28, the MON_DIS_CRCP_REV table contained a total of 492 records with an average of 5 surveys per section and an average of 3 surveys per construction event.

- Rutting metric: Rutting data are collected as multiple transverse profiles on each test section. Each transverse profile has between 10 and 30 measurement points in the transverse direction (across the lane), and profiles are collected at approximate 49.2-ft intervals along a test section. These data are used to estimate the rut depth based on either a 5.9-ft straightedge reference or a lane-width wire-line reference. Other parameters are also estimated from these data; however, the two types of rut depth referenced were the most relevant ones to the project in question. These data do not exactly match either of the standards identified within the NPRM, but they are believed to be more precise than AASHTO R48-10 and less precise than AASHTO PP70-14, with a less than true maximum bias due to the larger transverse measurement intervals as compared to that stated in AASHTO PP70-14.(22,23)

- The LTPP data for rutting were obtained from the MON_T_PROF_INDEX_SECTION table, which in SDR 28 contained 19,124 records. The section records contain average rut depth for each measurement location, which equates to eight transverse profile surveys per section on a given survey date, with an average of four survey datasets within a construction event.

- Faulting metric: Faulting data are collected using an FHWA-modified Georgia Faultmeter at 1-ft and 2.5-ft offsets from the outside slab edge. The recorded fault magnitude at each joint and crack is reported as the average of three measurements. Values are reported at each individual transverse joint and crack. These data are expected to be more precise than those required by the NPRM, which are collected under AASHTO R36-13 (allows for faulting to be collected manually on a 10-percent sample of the joints) or in an automated approach on all joints.(25)

  The data for faulting were obtained from the MON_DIS_JPCC_FAULT_SECT table. In SDR 28, this table contained average faulting for a total of 6,118 records. Of those records, 1,383 records were from cracks, and 4,735 records were from joints. There was an average of six surveys per section and an average of three surveys within a single construction event.

To review the pavement condition metrics, it was necessary to use the data collected in accordance with the LTPP standards to estimate the data as they would be collected in accordance with the NPRM. Most of the data identified either meet or exceed the precision of the data collection requirements identified within the NPRM.

LTPP DATA TRANSLATION TO NPRM DEFINITIONS

The methods that were used in translating the data collected for the LTPP program to the NPRM pavement condition metrics, as they would be collected on the LTPP test sections, are detailed in this section. These methods are presented by distress, with specific steps listed under each distress.

IRI Metric

- Multiplied the IRI_AVERAGE by 63.36 to convert from meter/kilometer to inch/mile.
- Averaged the IRI_AVERAGE value for all runs with the same PROFILE_DATE on a test section.

Cracking Metric

- For AC pavements, percent cracking was determined as follows and referred to as "AC-all" for the remainder of the report and analysis:

  a) Identified length of longitudinal cracking (wheel path and non-wheel path), edge cracking, and transverse cracking in meters and converted to feet along the test section, including:

     i. Sealed and unsealed cracks.
     ii. All severity levels.

  b) Multiplied length of longitudinal cracking in the wheel path from the above step by 2.5 ft, in accordance with AASHTO R55-10.[19]

  c) Multiplied length of non-wheel-path longitudinal cracking and transverse cracking by 1 ft from step (a).

  d) Multiplied the length of edge cracking from step (a) by 0.5 ft.

  e) Identified total area of fatigue and block cracking on the test section in square meters and converted to square feet.

  f) Summed the total cracking area (from steps (b–e)) for all distress types and severity levels for both sealed and unsealed cracks.

  g) Calculated the area of the section, in square feet, as the length of the section converted from meters multiplied by the full width of the section converted from meters.

  h) Divided the total area of cracking by the total area of the section and expressed as a percentage to the nearest whole number.

  In addition to the above methodology, the AC percent cracking metric was also determined (at the request of FHWA) based on the following:

    - Longitudinal cracking in the wheel path and fatigue cracking only; other types of cracking were not considered (non-wheel-path longitudinal cracking, edge cracking, and transverse cracking).
    - Methodology recommended in AASHTO Standard R 55-10, *Standard Practice for Quantifying Cracks in Asphalt Pavement Surface*.(19)

  This alternate methodology was pursued at the request of FHWA in light of possible changes in the Final Rule, from total area to area in wheel paths, which were ultimately implemented. In addition, the alternate methodology also supported other national- and State-level initiatives, including the HPMS Guide, Highway Economic Requirements Systems models, the Pavement Health Track analysis tool, and the NAtional Pavement COst Model. This alternate methodology is referred to as "AC-fatigue" for the remainder of the report. It is worthwhile noting that the same threshold values for this alternative methodology were used as with the previously presented percent cracking. For the alternate methodology, the following procedure was used:

    a) Identified length of longitudinal cracking in the wheel path in meters and converted to feet along the test section, including:
        i. Sealed and unsealed cracks.
        ii. All severity levels.
    b) Multiplied length of cracking from above step by 2.5 ft, in accordance with AASHTO R55-10.(19)
    c) Identified total area of fatigue cracking on the test section in square meters and converted to square feet.
    d) Summed the total cracking area for all distress types (longitudinal cracking in the wheel path from step (b) and fatigue cracking from step (c)) and severity levels for both sealed and unsealed cracks in the wheel paths.
    e) Calculated the area of the section in square feet as the length of the section converted from meters multiplied by the full width of the section converted from meters.
    f) Divided the total area of cracking by the total area of the section and expressed as a percentage to the nearest whole number.

- For JPCC pavements, percent cracking was determined based on the following guidelines:
    - The presence of corner breaks, D-cracking, and Alkali Silica Reactivity cracking were excluded.
    - A slab was considered cracked if it contained a fatigue (longitudinal and/or transverse) crack.

- If there were multiple cracks within a slab, that slab was counted as a cracked slab only once.
- All severity levels of associated cracking were considered and reported.
- The total percent of PCC cracked slabs was reported to the nearest whole percentage point.
- Partial slabs were considered as a full slab if the length of the partial slab was at least half the length of a regular section slab. If the partial slab length was less than half the length of a regular section slab, the slab was not considered as a slab for the calculations.

Attempts were made to automate the computation of percent cracking for JPCC pavements, as was the case for AC and CRCPs. However, the results of a small pilot study conducted in support of the project, which compared the difference between percent cracking determined using a manual approach versus an automated approach, conclusively showed that there was too great of a nonsystematic difference, as shown in table 4, to allow for estimating JPCC percent cracking based on the automated approach.

Accordingly, cracking percent for JPCC pavements was determined using the following method based on LTPP distress maps:

a) Manually counted total number of slabs and number of cracked slabs using the criteria above from the distress map or the distress map photos for each survey.

b) Determined percentage cracking as shown in figure 1**.**

$$\%\, cracked\ slabs = \frac{Number\ of\ cracked\ slabs}{Number\ of\ total\ slabs} * 100$$

Figure 1. Equation. Percentage of cracked slabs.

- For CRCPs, percent cracking was determined based on the following guidelines:
  - All severity levels of associated cracking were considered and reported.
  - The area of punchouts, longitudinal cracking, and/or patching for any severity level was reported as a percent.
  - The total percent of cracking was reported to the nearest whole percentage point.

Table 4. Comparison of JPCC percent cracking—automated versus manual.

Surface Type	Section	Survey Date	Number of Transverse Cracks	Length of Longitudinal Cracking (ft)	Cracked Slabs Automated (%)	Cracked Slabs Manual (%)
JPCP	133017	5/10/2012	0	41.4	8.0	12.0
JPCP	313023	4/20/1995	21	11.5	57.6	63.6
JPCP	063042	4/13/2012	25	0.9	51.5	75.8
JPCP	123811	8/31/1994	16	2.5	60.0	64.0
JPCP	320202	3/27/1996	51	161.2	100.0	100.0
JPCP	320205	3/26/1996	75	33.0	81.8	100.0
JPCP	123804	7/17/1991	16	0.0	61.5	61.5
JPCP	373008	1/31/1996	0	88.3	58.3	20.8
JPCP	063019	3/8/2002	12	0.0	37.5	37.5
JRCP	544004	6/4/1996	39	0.0	100.0	100.0
JRCP	364017	4/15/1997	38	10.8	100.0	100.0
JRCP	184042	7/1/2004	7	0.0	38.5	38.5
JRCP	204053	7/17/2001	12	0.0	100.0	66.7
JRCP	054019	4/17/2012	0	13.3	12.1	3.0
JRCP	394018	4/30/1991	49	0.0	83.3	100.0
JRCP	421691	10/31/1989	8	14.9	62.5	62.5
JRCP	314019	7/31/1991	19	0.0	90.9	100.0
JRCP	394031	7/15/1994	5	0.0	50.0	37.5

JPCP = jointed plain concrete pavement; JRCP = jointed reinforced concrete pavement.

Cracking percent for CRCP was established using the following estimated method:

a) Estimated the area, in square feet, of cracking as follows, based on known items from the LTPP database such as lane width, section length, number of punchouts, length of longitudinal cracking (with and without sealant in good condition), and number of patches and associated area as shown in figure 2 through figure 4.

$$Area\ of\ punchouts\ (sq.ft.) = number\ of\ punchouts\ (all\ severities) \times 0.5\ \times lane\ width\ (ft) \times 2\ ft$$

Figure 2. Equation. Area of punchouts.

$$Area\ of\ patches\ (sq.ft.) = \frac{\sum area\ of\ all\ patches\ at\ all\ severities\ \ (m^2)}{0.0929\ \left(\frac{m^2}{ft^2}\right)}$$

Figure 3. Equation. Area of patches.

$$Area\ of\ longitudinal\ cracking\ (sq\ ft) = \frac{length\ of\ longitudinal\ cracking\ (m)}{0.3048\ \left(\frac{m}{ft}\right)} \times 1\ ft$$

Figure 4. Equation. Area of longitudinal cracking.

While the area of punchouts was originally going to be computed per the above equation, the decision was made to do manual takeoffs from the distress map or the distress map photos for each survey, as this would produce a more accurate estimate of the punchout area.

b) Combined total area of cracking (square feet), which was equal to the summation of punchouts, patches, and longitudinal areas above.

c) Estimated the percent cracking as shown in figure 5.

$$Percent\ cracking = \frac{area\ from\ item\ b.\ (sq\ ft)}{lane\ width\ (ft) \times section\ length\ (ft)}$$

Figure 5. Equation. CRCP percent cracking.

Rutting Metric

- Averaged the LLH_DEPTH_1_8_MEAN and the RLH_DEPTH_1_8_MEAN to develop the average rut depth for the section.
- Divided the average rut depth by 25.4 to convert from millimeters to inches.
- Rounded the result to the nearest 0.05 inch.

Faulting Metric

- Faulting data were limited to data identified as joint data within the MON_DIS_JPCC_FAULT_SECT table.
- AVG_WHEELPATH_FAULT value was divided by 25.4 to convert from millimeters to inches.
- The result was rounded to the nearest 0.05 inch.

PROJECT DATABASE

A project database containing data from all LTPP test sections was created for each NPRM pavement condition metric, which included the translated version of LTPP pavement performance data collected as of LTPP SDR 29. This project database also included the overall pavement condition ratings in terms of good, fair, and poor, as determined using the NPRM pavement condition metric thresholds—a number of threshold values changed in the Final Rule, as is addressed later in the report. Further, other data were incorporated into the project database for various purposes, including establishing pavement families or for distinguishing the response of the condition metric over time. These data included climate zone, functional classification, and pavement type.

The purpose of the project database was to provide a pool of data that could be used in the various analyses conducted as part of the review and validation of the proposed performance measures. Using the project database, smaller and more targeted datasets were created for the analyses discussed in the next two chapters. For example, one such dataset was developed for each surface type and pavement metric, which met a minimum set of requirements as illustrated below:

- Four data collection events/surveys within one construction event for the section.
- Documented distress (e.g., nonzero cracking).
- Well-documented maintenance events.

The specific datasets created from the project database are also discussed individually in the next two chapters for each analysis.

CHAPTER 4. TEMPORAL, TREATMENT, AND THRESHOLD IMPACTS ON PERFORMANCE MEASURES

The results of the literature review indicated that the performance measures were comprehensive with respect to the state of the practice, balanced in that they comprise individual metrics for IRI, cracking, rutting, and faulting, and they show the expected performance trend over time (albeit largely static as shown later in the report). In light of these findings, the following analyses were undertaken to validate the performance measures:

- Review of pavement metrics and performance measures over time.
- Comparison of pavement metrics and performance measures against M&R activities.
- Review of pavement metrics and performance measures against thresholds identifying performance.

Each of these three analyses—including approach, findings, and conclusions—are detailed after an overview of the datasets used in support of the analyses.

DATASET OVERVIEW

A summary aggregate statistical approach was used for the analyses presented in this chapter. A key reason for selecting this approach was to get a grasp on general trends in the data to make sure that the data were suitable for the planned analyses as well as for the more indepth analyses presented in chapter 5. The general trends included:

- Changes in the pavement condition metrics and performances measures over time.
- Changes in the pavement condition metrics and performance measures against M&R activities.

The first step in performing the analysis of each condition metric was to develop a dataset for that metric from the project database, which was introduced at the very end of chapter 3. Toward this end, LTPP test sections were considered if there were at least four surveys of the metric in question between two consecutive construction (M&R) events—those sections with less than four surveys were removed from consideration. A random sample of test sections was then selected from the pool of available test sections for each combination of metric and pavement type. Accordingly, the resulting random samples or datasets are referenced throughout this report by the metric name and pavement type.

Table 5 provides the summary statistics for the datasets for each metric by pavement type. In addition, the table also confirms the availability of the data required for analyzing trends both over time and against M&R activities by the number of surveys within a construction event and the number of construction events, respectively.

Table 5. Summary statistic for metric datasets.

Statistic	IRI	Cracking AC-All	Cracking AC-Fatigue	Cracking JPCC	Cracking CRCP	Rutting	Faulting
Average measurement	86.2 inch/mi	15.5%	6.7%	15.8%	1.2%	0.18 inch	0.04 inch
Average number of surveys within construction event	9	3	3	3	3	5	3
Maximum number of surveys within construction event	39	17	17	27	9	20	27
Average number of construction events	2	2	2	2	2	3	2
Maximum number of construction events	12	15	15	12	7	12	7
Average time since last construction event, years	7.6	6.0	6.0	8.1	13.8	6.6	11

Since HPMS is the data source to be used for determination of the performance measures, it was important that the datasets used in the LTPP performance measures validation effort were, to the extent possible, a representative sample of the HPMS data. To evaluate this, two stratification factors were considered to compare the LTPP datasets to the 2013 HPMS dataset—the 2014 and 2015 HPMS datasets were not available at the time the analyses presented in this chapter were conducted. These factors were climate zone and urban versus rural. The climate zone for the LTPP datasets was determined based on the following classifications:

- LTPP test sections were classified as "wet" if the average site precipitation was greater than 20 inches/yr and "dry" otherwise.

- LTPP test sections were classified as "freeze" if the average site freeze index was greater than 46 °C – degree days and "no freeze" otherwise.

Table 6 provides the comparison of the distributions of the 2013 HPMS dataset and the LTPP datasets for IRI, AC cracking, JPCC cracking, CRCP cracking, rutting, and faulting, respectively, by climate zone. The distribution of the LTPP test sections generally compares well with that of the 2013 HPMS dataset, but with the wet-no-freeze zone being slightly underrepresented and the dry-freeze zone being slightly overrepresented. Similarly, table 7 provides the comparison of the distribution of the 2013 HPMS dataset and LTPP datasets for IRI, AC cracking, JPCC cracking, CRCP cracking, rutting, and faulting, respectively, for urban versus rural composition. Urban sections are underrepresented in the LTPP sections, but this was to be expected, as most of the LTPP sections are located in rural areas.

Table 6. Comparison of HPMS and LTPP datasets climate distribution.

Dataset	Wet-Freeze (%)	Wet-No-Freeze (%)	Dry-Freeze (%)	Dry-No-Freeze (%)
2013 HPMS	41	25	20	14
IRI	41	8	34	17
AC cracking	40	13	29	18
JPCC cracking	41	6	37	16
CRCP cracking	24	21	34	21
Rutting	40	11	32	16
Faulting	37	10	26	27

Table 7. Comparison of HPMS and LTPP datasets rural versus urban distribution.

Dataset	Rural (%)	Urban (%)
2013 HPMS	62	38
IRI	89	11
AC cracking	95	5
JPCC cracking	78	22
CRCP cracking	80	20
Rutting	92	8
Faulting	85	15

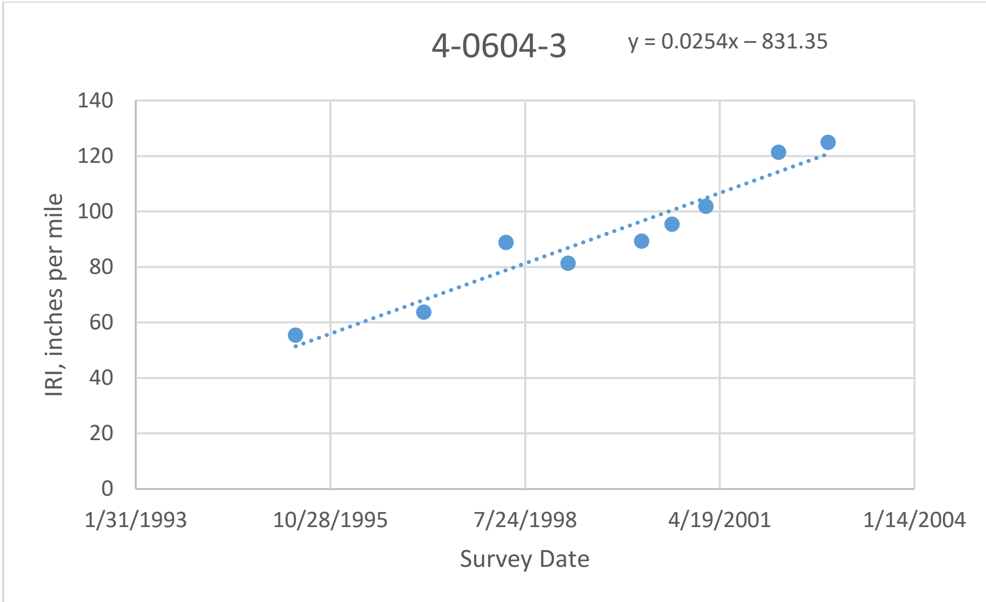
COMPARISON OF METRICS AND RATINGS OVER TIME

Pavement Condition Metrics

The initial analysis considered the pavement metrics individually, and its objective was to review the metric trends over time by considering surveys between two consecutive construction events using the LTPP datasets developed for each metric. As part of this analysis, the numeric values from the surveys were plotted over time, and a linear trend line was plotted for each section as illustrated in figure 6. The trend was then classified as increasing (i.e., worsening condition), decreasing (improving condition), or no change (steady-state condition) based on the slope of the trend line.

A summary of the metric analysis results is provided below:

- IRI metric: Table 8 summarizes the trend over time for the IRI metric. As shown in this table, overall LTPP test sections have an increasing trend in IRI 92 percent of the time, while only 8 percent of the test sections have a decreasing IRI slope. These results appear to be logical, and they were expected (i.e., an increase or worsening of IRI over time within a given construction event). The small percentage of test sections where the IRI decreases is attributed to factors such as measurement error and differences in the date and time of data collection from year to year.



Source: FHWA.

Figure 6. Scatterplot. Example of trend line analysis for IRI on section 040604, construction number 3.

Table 8. IRI changes within construction events by pavement type.

Pavement Type	Increase (%)	Decrease (%)
AC	94	6
JPCC	78	22
CRCP	95	5
Network	92	8

- Cracking metric: The analysis for the AC pavement cracking metric over time is summarized in table 9. For the case of AC pavement cracking based on the entire lane area (as defined in the NPRM; referred to hereafter as "AC-all"), 97 percent of the test sections have an increasing trend in cracking over time, while 2 percent have a decreasing trend, and 1 percent have no change. Alternately, for the case of AC pavement cracking based on the wheel paths area only (in line with Final Rule; hereafter referred to as "AC-fatigue"), 91 percent of the test sections have an increasing trend in cracking over time, while 5 percent have a decreasing trend, and 4 percent have no change. Again, both sets of results are logical, and they were expected. Likewise, the small percentage of test sections where cracking decreases is attributed to factors such as measurement error and differences in the date and time of data collection from year to year.

Table 9. Cracking changes within construction events for AC pavements.

Cracking Type	Increase (%)	Decrease (%)	No Change (%)
AC-all	97	2	1
AC-fatigue	91	5	4

In the case of JPCC pavements, 82 percent of the test sections have an increasing trend of cracking with time, while 10 percent show a decrease, and 8 percent have no change. These trends are mostly logical in that cracking for the largest percentage of test sections increases over time. Those test sections with a decreasing trend in cracking were found to be in many cases the result of one measurement being larger and the remaining measurements holding constant over time. There was no discernible cause for these larger measurements, but they could be a result of the interpretation differences or measurement errors, among others.

Consistent with the AC and JPCC pavements, but somewhat less definitive, CRCP cracking also shows a predominant increasing trend of cracking with time. More specifically, 71 percent of the test sections showed an increasing trend in cracking, while 29 percent had no change. This seems logical (i.e., CRCP cracking either increases or remains constant over time). However, the CRCP dataset had a limited number of test sections, and for those test sections where cracking did not increase over time, a large percentage (85 percent) of them were based on only 2 yr (not necessarily consecutive) of data. These sections with only 2 yr of data were kept in the dataset because of the small number of CRCP test sections meeting the criteria for inclusion in the dataset. If they are removed from the dataset, 94 percent of the CRCP test sections show an increase in percent cracking over time, but the dataset is significantly reduced (by 25 percent) in size.

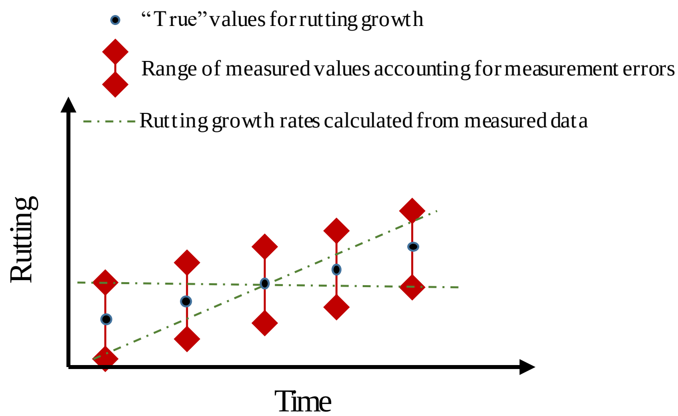
- Rutting metric: The analysis of the rutting metric over time showed 69 percent of the AC pavement test sections with an increasing trend in rutting over time, while 23 percent have a decreasing trend, and 8 percent have no change. Table 10 shows the breakdown of results according to pavement family within the AC pavement type.

Table 10. Rutting changes within construction events by AC pavement type.

Pavement Type	Increase (%)	Decrease (%)	No Change (%)
AC	70	23	7
AC over AC	73	18	9
AC over PCC	62	29	9
Total	69	23	8

While it is expected that rutting will increase with time if no M&R is applied to the pavement, it is important to understand that the expected average rate of change in rutting is less than the measurement error. The *Guide for the Local Calibration of the Mechanical-Empirical Pavement Design Guide* reports a reasonable standard error of the estimate for rutting to be 0.10 inch, while the average rate of change for rutting can be less than 0.01 inch/yr.[(28)] Therefore, it is possible for test sections to show a decreasing trend in rutting over time as a result of measurement errors. This is most likely the cause for 23 percent of the test sections showing a decrease in rutting.

The issue of measurement error is further expanded in figure 7. As shown in this figure, for every measurement, there is a "true" value that represents the actual value. Each measurement also has a range of likely measurable values, which can be attributed to errors such as measurement errors and errors introduced by averaging many measurements into one representative value for a segment in the case of LTPP. Errors in linear referencing from year to year are another possible consideration for highway agencies. Due to this plausible interval of measurements, it is conceivable to report a variety of growth rates from the measured data depending on where in the interval the measured value falls in comparison to the true value. There are two possible relationships for growth rates as a result of the intervals—one with a positive and one with a negative trend, although the true rutting values show a positive growth rate. This example should help to further illustrate and explain some of the decreasing trends in rutting over time.



Source: FHWA.

Figure 7. Graph. Rutting growth.

- Faulting metric: The results of the analysis of the faulting metric over time showed that 70 percent of the JPCC test sections have an increasing trend of faulting with time, while 21 percent have a decreasing trend, and 9 percent of sections have no change. Table 11 provides the breakdown of the results by pavement family with the JPCC pavement type.

Table 11. Faulting changes within construction events by JPCC pavement type.

Pavement Type	Increase (%)	Decrease (%)	No Change (%)
JPCP	69	23	8
JRCP	80	10	10
Total	70	21	9

It is important to note that LTPP faulting measurements are reported to the nearest 0.05 inch and often fluctuate between two values (e.g., 0 to 0.05 inch). This fluctuation can be caused by measurement error or differences in the time of data collection.

According to the literature, a reasonable standard error of the estimate for faulting is 0.05 inch.[28] In addition, the faulting value for a given test section is the average faulting at all joints in that section, which may increase the variability of the reported faulting value. Consequently, the fluctuation in faulting measurements can result in a decreasing faulting trend over time.

The analyses of the metrics over time also considered stratification by route type (interstate, other, State, and United States) and climate zone (wet-freeze, wet-no-freeze, dry-freeze, and dry-no-freeze). Other than a couple of exceptions, the findings showed that the trends for the four metrics were independent of stratification factor (i.e., larger percentage of test sections have an increasing trend of metric in question over time). The two exceptions were the following:

- Rutting appears to be more of an issue in the wet-no-freeze zone, as rutting increased with time for 90 percent of the AC pavement test sections in this climate zone.

- Faulting is more of an issue in the wet zones, as faulting increased with time for 80 percent of the JPCC pavement test sections in these climate zones.

Overall Pavement Condition Ratings

The next set of analyses considered the changes in overall pavement condition over time. The determination of the overall pavement condition ratings was based on the individual metrics presented in the previous section. The overall pavement condition rating combines IRI, cracking, and rutting for AC pavements; IRI, cracking, and faulting for JPCC pavements; and IRI and cracking for CRCPs. To combine the two or three individual metrics together into one overall pavement condition rating, the individual metrics were grouped together. For purposes of the study, these survey groupings required that the individual metric surveys were taken within 1 yr of the others—these requirements were established by the project team.

Once the survey groupings were in place, the individual metric conditions, as assigned based on the thresholds in table 1, were then combined to determine the overall pavement condition rating as follows:

- For AC and JPCC, the pavement was classified as good condition if all three metrics were in good condition. The pavement was classified as poor condition if two or more of the metrics were in poor condition. All other combinations of metric conditions classified the pavement as fair.[4]

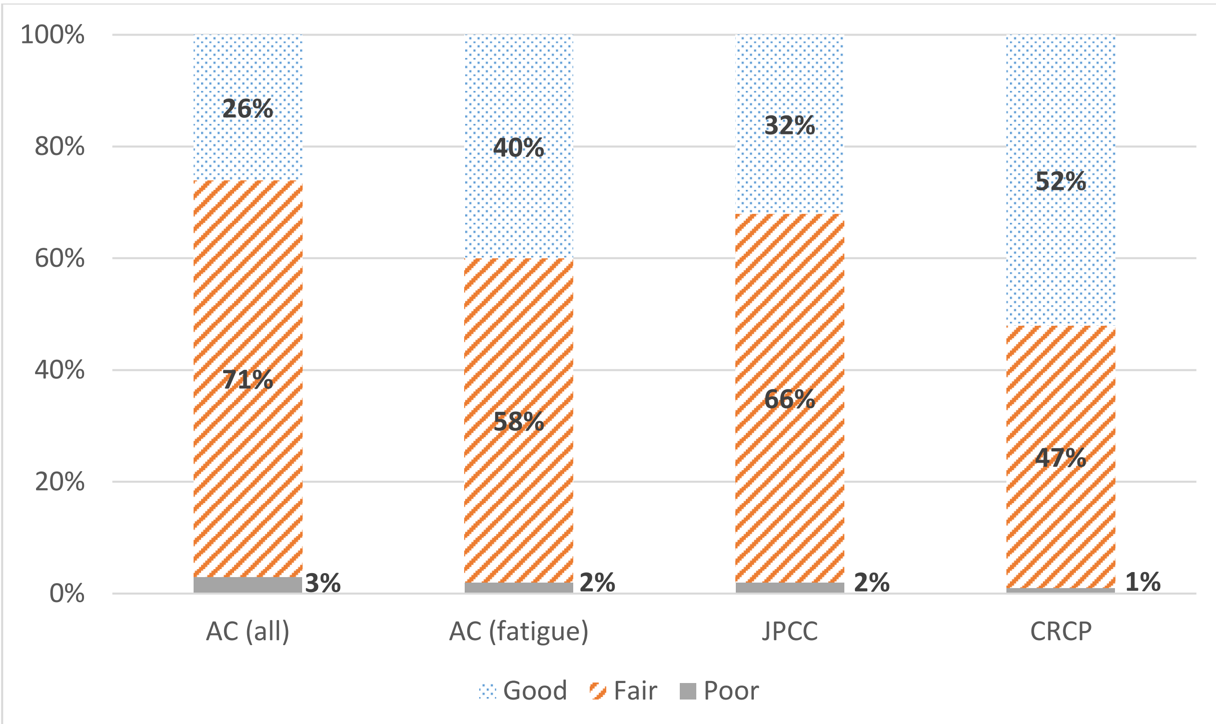
- For CRCP, if both metrics were in good condition, the pavement was classified as good. The pavement was classified as poor if both metrics were in poor condition. All other combinations of metric conditions classified the pavement as fair.[4]

A summary of the survey groupings is provided in table 12, including the number of survey groupings in each condition category. Figure 8 presents the overall pavement condition ratings for AC-all, AC-fatigue, JPCC, and CRCPs. As shown in this figure, there are very few LTPP pavement survey groupings in poor condition (less than 3 percent) and, with the exception of CRCP, the majority of pavement survey groupings are in fair condition.

Table 12. Survey grouping summary.

Pavement Type	Number of Survey Groupings	Good*	Fair*	Poor*
AC-all	6,236	1,591	4,451	194
AC-fatigue	6,236	2,505	3,601	130
JPCC	3,142	1,010	2,057	75
CRCP	252	132	117	3

*Indicates overall pavement condition rating.



Source: FHWA.

Figure 8. Bar graph. Overall condition rating.

Once derivation of the overall pavement condition ratings based on the individual condition metrics was completed, the trends in the overall pavement condition ratings over time within a construction event were reviewed. Section groupings with at least three overall pavement conditions ratings within a construction event were considered in this analysis. A random number of sections were selected for analysis from the section groupings based on the number of available groupings by pavement type. The trend of overall pavement condition ratings was reviewed to determine if it followed a logical and expected trend (i.e., good to fair to poor). Table 13 shows the number of section groupings analyzed by pavement type and the percent of those sections that followed the expected trend. The overall pavement condition rating performed as expected for 90 percent or more of the sections, except for JPCC pavements, which performed as expected for 83 percent of the cases sections.

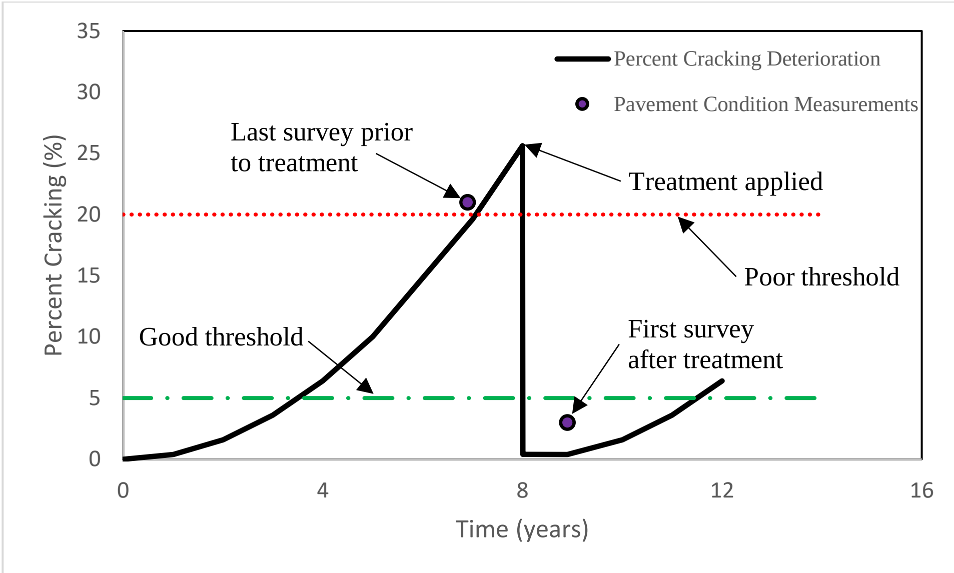
Table 13. Overall pavement condition ratings over time.

Pavement Type	Cracking Type	Number of Sections	Logical (%)
AC	All	100	91
AC	Fatigue	100	90
AC on AC	All	50	90
AC on AC	Fatigue	50	96
AC on PCC	All	50	92
AC on PCC	Fatigue	50	98
JPCC	JPCC	150	83
CRCP	CRCP	56	98

Section groupings that did not follow the expected logical trend were reviewed in detail, including looking at the individual metrics that made up the overall pavement condition rating, to determine if there were data issues or the reason for the unexpected trend. Most of the section groupings that did not follow the expected logical trends were a result of one overall pavement condition rating not following the expected trend. Further investigation revealed that for the AC pavements, the main cause was the rutting values fluctuating between 0.15 and 0.2 inch, which varies the condition of rutting between good and fair. For the JPCC pavements, the main cause was faulting values fluctuating between 0 and 0.05 inch, which varies the condition of faulting between good and fair. In addition, for some of the sections, the IRI and cracking metrics fluctuated around the good, fair threshold for all pavement types. It was hypothesized that these small variations were likely attributable to the precision of the measurement procedure.

COMPARISON OF METRICS AND RATINGS AGAINST M&R ACTIVITIES

The objective of the analysis summarized in this section was to perform a comparison of the time series trends of pavement condition metrics and overall condition ratings and hence performance measures against documented M&R applications. A valid performance measure must be impacted by M&R treatments. Therefore, the trend in individual metrics followed by the overall pavement condition rating over time was reviewed against recorded M&R treatments to determine whether it demonstrated any type of change in response to those treatments. For this analysis, the last survey prior to the M&R treatment was compared to the first treatment after the M&R treatment as illustrated in figure 9. The surveys were not necessarily taken immediately before and after the M&R treatments. In some cases, 1 yr or more transpired between the placing of the M&R treatment and the survey date.



Source: FHWA.

Figure 9.Graph. Example of survey timing in comparison to treatment.

Pavement Condition Metrics

Initially, pavement sections with a construction event change were evaluated, and the results are presented in this section. The construction event treatments were grouped into categories based on similarity. For example, skin patching, pothole patching, and other types of patching were grouped together as patching. If there were multiple improvements for a single construction event, the improvements were grouped based on what would be expected to have the most influence on the surface. For example, if surface treatment and shoulder restoration were applied at the same time at a test section, the event was classified as surface treatment, since shoulder restoration has no impact on the metrics or overall condition rating.

Next, the trend of the individual metric was classified as increasing, decreasing, or no change if the metric increased, decreased, or did not change, respectively. The change in the metric resulting from the application of the treatment was then quantified both in percentage and magnitude terms. The results of this effort are detailed below by metric.

- IRI metric: The initial review of the effect of treatment types on IRI showed that treatments such as mill and overlay had the most significant effect (i.e., reduction) on IRI. Crack seal, patching, and surface treatments, on the other hand, mostly increased IRI, which is not unexpected, since these treatments are not placed to improve ride quality. Next, the percent change of the IRI measurement resulting from the various treatments was investigated. Table 14 shows the number of sections where the IRI was reduced or increased and the IRI percent change (in parentheses) as a function of treatment type. The overlay treatment, for example, had 58 sections that improved the IRI by an average of 47 percent, which represents a 74-inch/mi reduction. This table also shows that the fractures with overlay, mill and overlay, and overlay treatments have the largest improvement on IRI, which is expected. Treatments that result in an increase in IRI most often are crack sealing, surface treatment, and patching.

Table 14. Number of sections experiencing change in IRI due to M&R application.

Treatment Type	Reduced IRI	Increased IRI
Crack seal	15 (3%)	34 (12%)
Fracture w/overlay	6 (53%)	0 (N/A)
Grinding	9 (32%)	0 (N/A)
Joint seal	6 (3%)	4 (5%)
Mill and overlay	38 (42%)	3 (11%)
Overlay	58 (47%)	3 (14%)
Patch	45 (5%)	86 (15%)
PCC overlay	4 (26%)	2 (4%)
Shoulder restoration	0 (N/A)	3 (8%)
Surface	9 (1%)	18 (14%)

Note: The value in parentheses is the percent change in the IRI value after application of the treatment.

- Cracking metric: In the case of AC pavements, mill, and overlay, overlay and surface treatments improved cracking most often, while crack seal and patching increased cracking. (Note: The calculation of percent cracking includes sealed cracks; therefore, crack sealing is not expected to reduce the amount of cracking.) Table 15 and table 16 show the number of sections where the percent cracking was reduced, increased, or did not change and the cracking percent difference (in parentheses) for AC-all and AC-fatigue measurements, respectively. Mill and overlay, for example, improved cracking by 91 and 97 percent, which represented percent cracking reductions of 33 and 18 percent, respectively. The tables also show that mill and overlay, overlay, and surface treatment have the largest improvement of AC cracking. The magnitude of the increases in percent cracking was much smaller than the magnitude of the percent cracking decreases. The improvement in cracking was not 100 percent for the overlay treatments because, in some cases, the surveys were not performed directly after the placement of the treatment. That is to say, there was a time lag between the placement of the treatment and the next survey, allowing for some cracking to either develop or reflect through the surface.

Table 15. Number of sections experiencing change in percent cracking (AC-all) due to M&R applications.

Treatment Type	Reduced Cracking	Increased Cracking	No Change
Crack seal	4 (30%)	59 (587%)	0
Grinding	0 (N/A)	2 (43%)	0
Mill and overlay	49 (91%)	6 (202%)	0
Overlay	43 (89%)	4 (126%)	9
Patch	38 (21%)	67 (123%)	7
Surface	34 (69%)	7 (380%)	1

Note: The value in parentheses is the percent change in the percent cracking value after application of the treatment.

Table 16. Number of sections experiencing change in percent cracking (AC-fatigue) due to M&R applications.

Treatment Type	Reduced Cracking	Increased Cracking	No Change
Crack seal	7 (54%)	46 (325%)	10
Grinding	1 (3%)	1 (7%)	0
Mill and overlay	46 (97%)	1 (100%)	8
Overlay	42 (93%)	1 (100%)	13
Patch	33 (34%)	66 (276%)	13
Surface	24 (72%)	6 (135%)	12

Note: The value in parentheses is the percent change in the percent cracking value after application of the treatment.

In the case of JPCC pavements, patching reduced cracking the most, but it also increased percent cracking the most. This may be a result of the different sizes of patches used and how a patch is classified. For example, if a patch is large enough to be considered a partial slab, it is classified as a new slab if the length of the partial slab is at least half the length of the regular slab of the section. Table 17 shows the number of sections where the percent cracking was reduced, increased, or did not change and the percent difference in cracking percent (in parentheses) for JPCC pavements as a function of treatment type. It should be noted that when grinding increased the amount of cracking, the average time from the treatment date to the survey date was 1.5 yr. Therefore, this increase in cracking is not unexpected.

Table 17. Number of sections experiencing change in percent cracking (JPCC) due to M&R applications.

Treatment Type	Reduced Cracking	Increased Cracking	No Change
Crack seal	2 (15%)	9 (59%)	4
Grinding	2 (75%)	5 (120%)	5
Grooving	0 (N/A)	2 (22%)	0
Joint seal	6 (47%)	13 (117%)	13
Patch	19 (47%)	27 (150%)	35
Shoulder	2 (14%)	1 (62%)	2
Slab replacement	5 (41%)	2 (58%)	2

Note: The value in parentheses is the percent change in the percent cracking value after application of the treatment.

Table 18 shows the number of sections where the percent cracking was reduced, increased, or did not change and the percent difference in percent cracking (in parentheses) for CRCP as a function of treatment type. As shown, PCC overlays reduced cracking by 100 percent, which represents a reduction in percent cracking of 9.5 percent. This table also shows that PCC overlays had the largest effect on cracking percent reduction, while patching had the largest impact on cracking percent increase.

For CRCP, PCC overlays reduced cracking the most, while patching increased cracking the most. The calculation of percent cracking includes patching for CRCPs; therefore, patching does not reduce the amount of cracking but instead increases the amount of cracking. There is only one section where patching reduces cracking. This is a result of the percent cracking decreasing from 1 to 0 percent. It would not be anticipated to see patching not change the percent cracking either, although 47 percent of the time when patching was placed, the percent cracking did not change. These test sections were investigated, and the findings are detailed below.

Table 18. Number of sections experiencing change in percent cracking (CRCP) due to M&R applications.

Treatment Type	Reduced Cracking	Increased Cracking	No Change
Crack seal	0 (N/A)	0 (N/A)	3
Grooving	0 (N/A)	1 (100%)	0
Joint seal	0 (N/A)	0 (N/A)	5
Patch	1 (100%)	24 (122%)	22
PCC overlay	4 (100%)	1 (100%)	8
Shoulder	0 (N/A)	0 (N/A)	2

Note: The value in parentheses is the percent change in the percent cracking value after application of the treatment.

The percent cracking calculation for CRCP includes the summation of the area of punchouts, patches, and longitudinal cracking. It would be expected that applying a patch would increase the percent cracking. However, in some cases, the area of patching placed is smaller than the area of punchouts, patches, and longitudinal cracking prior to the latest maintenance; in these cases, the patching does not appear to increase the percent cracking by at least half of a percentage. Therefore, generally patches that are less than 30 sq ft will not affect the percent cracking for the typical LTPP test sections used in this analysis.

- Rutting metric: Table 19 shows the number of sections where the rutting was reduced, increased, or did not change and the percent difference (in parentheses) for rutting measurements as a function of treatment type. For example, the mill and overlay treatment reduced rutting by 65 percent, which represents a 0.21-inch reduction in rutting. As also shown in table 19, the mill and overlay and overlay treatments result in the largest improvement in rutting. In terms of the AC pavement rutting metric, the mill and overlay and overlay treatments were found to consistently improve rutting, while the effect of other treatments was not consistent—in some cases rutting decreased, while in others it increased. Crack seal and patching treatments tended to show more of an increase in rutting rather than a decrease. However, although rutting increased after these treatments, it does not necessarily mean that the treatments are detrimental to rutting. These treatments are not meant to address rutting, and therefore the increase in rutting after application of the treatments may be more attributable to the lapse in time between the placement of the treatment and the measurement survey and not the treatment itself. Overall, these findings are reasonable in that the treatments improving rutting the most are the ones expected. The treatments that are expected to address and improve rutting (e.g., overlays) have a reduction in rutting about three times greater than the increase in rutting magnitude after crack seal and patching.

Table 19. Number of sections experiencing change in rutting due to M&R applications.

Treatment Type	Reduced Rut Depth	Increased Rut Depth	No Change
Crack seal	11 (40%)	38 (62%)	38
Grinding	3 (50%)	0 (N/A)	1
Mill and overlay	47 (65%)	1 (50%)	0
Overlay	33 (64%)	4 (71%)	4
Patch	17 (27%)	36 (72%)	43
Shoulder restoration	1 (33%)	0 (N/A)	0
Surface	9 (47%)	16 (46%)	14

Note: The value in parentheses is the percent change in the rutting value after application of the treatment.

- Faulting metric: Table 20 shows the number of sections where the faulting was reduced, increased, or did not change and the percent difference (in parentheses) for faulting measurements as a function of treatment type. For example, grinding reduced faulting by 88 percent, which represents a 0.10-inch reduction in faulting, and reduced faulting 54 percent of the time. For JPCC pavements, grinding was found to improve faulting the most, while joint sealing and patching increased faulting the most. Grooving also shows a reduction in faulting that was not expected, but this is based on a small sample size (two sections). Besides grinding, the effect of the other treatments is not consistent—the same treatment can either increase or decrease faulting about the same magnitude. Joint sealing, shoulder restoration, and patching, to an extent, are not expected to address faulting, which can account for the inconsistency. The changes in faulting measurements in these cases are likely not attributed to the actual treatments but more likely to the precision in faulting measurements or time lapse between measurements.

Table 20. Number of sections experiencing change in faulting due to M&R applications.

Treatment Type	Reduced Faulting	Increased Faulting	No Change
Crack seal	0 (N/A)	0 (N/A)	4
Grinding	7 (88%)	0 (N/A)	6
Grooving	2 (50%)	0 (N/A)	1
Joint seal	4 (85%)	4 (83%)	17
Patch	8 (80%)	9 (83%)	27
Shoulder restoration	2 (75%)	1 (100%)	7
Slab replacement	3 (67%)	1 (50%)	4

Note: The value in parentheses is the percent change in the faulting value after application of the treatment.

Overall Pavement Condition Ratings

The next set of analyses considered the effects of M&R treatments on the overall pavement condition. The survey groupings as described in the previous report sections were again used for this analysis. Table 21 through table 24 show how the overall pavement condition rating was affected by treatment type, with the effects classified as improved rating, reduced rating, or no change in rating. These effects are based on the use of the NPRM thresholds. For the most part, these tables show that the overall pavement condition rating is largely unaffected by treatment, as reflected by the large percentage of no change. This is likely a function of the combination of metrics and the large percentage of overall pavement condition ratings classified as fair. For example, for an AC pavement to be rated good, the three individual metric ratings must be good, while a poor rating requires two or more of the individual metric ratings to be poor and thus all remaining pavements rated as fair. The overall pavement condition rating is only classified as good or poor if the pavement is truly in good or poor condition, respectively. It should be noted that the crack seal, shoulder, and slab replacement treatments are based on limited data.

Table 21. Overall pavement condition between construction events for AC-all.

Treatment Type	No Change (%)	Improve (%)	Reduce (%)
Crack seal	85	7.5	7.5
Grinding	80	20	0
Overlay	50	50	0
Patch	78	2	20
Surface	80	13	7
Overall	79	8	13

Table 22. Overall pavement condition between construction events for AC-fatigue.

Treatment Type	No Change (%)	Improve (%)	Reduce (%)
Crack seal	81	2	17
Grinding	91	9	0
Mill and overlay	21	78	1
Overlay	33	66	1
Patch	76	5	19
Surface	78	11	11
Total	64	24	12

Table 23. JPCC overall pavement condition between construction events.

Treatment Type	No Change (%)	Improve (%)	Reduce (%)
Crack seal	86	0	14
Grinding	72	17	11
Joint seal	88	5	7
Patch	90	0	10
Shoulder	60	0	40
Slab replacement	50	17	33
Total	84	4	12

Table 24. CRCP overall pavement condition between construction events.

Treatment Type	No Change (%)	Improve (%)	Reduce (%)
Patch	91	0	9
PCC overlay	15	85	0
Total	70	24	6

However, this is not completely unexpected. Based on the previous metric analysis conducted showing how each metric is affected by various treatment types, it was determined that not all metrics are affected by all treatment types. That is to say, treatments are sometimes applied to address a single distress or issue and may not improve the condition of the other metrics. With that said, by combining two (in the case of CRCP) or three (in the case of AC and JPCC) metrics to form an overall condition rating, an improvement in the overall condition rating is not always expected because of how the overall pavement condition rating is determined. For a pavement section to be classified as good, either both metrics for CRCP or all three metrics for AC and JPCC need to be good. Therefore, it is feasible to apply a treatment and not have the overall condition rating of the pavement section improve as a result. As observed in the review of the condition metrics, not all the condition metrics were positively affected by the various treatment types.

Consider the following example of two pavement sections to illustrate this finding. The first pavement section is an AC pavement section that initially has an IRI of 107 inch/mi, rutting of 0.8 inch, and cracking of 4.5 percent. The IRI condition is fair, the rutting condition is poor, and the cracking condition is good. The overall condition for this section is therefore fair. To address the rutting issue, an overlay is placed on the section. After the overlay, the pavement section has an IRI of 76 inch/mi, rutting of 0.15 inch, and cracking of 1.2 percent. The IRI condition is good, the rutting condition is good, and the cracking condition is good. Therefore, the overall condition for this section is now good, and the overlay has provided an improvement.

Now consider a second AC pavement section that initially has an IRI of 85 inch/mi, rutting of 0.65 inch, and cracking of 1 percent. The IRI condition is good, the rutting condition is poor, and the cracking condition is good. The overall condition for this section is fair. To address the rutting issue, an overlay is placed on the section. After the overlay, the pavement section has an IRI of 72 inch/mi, rutting of 0.2 inch, and cracking of 0 percent. The IRI condition is good, the rutting condition is fair, and the cracking condition is good. The overall condition for this section remains fair, although the overlay did improve each of the metric performances. This provides an example of one way the overall pavement condition is not affected by a treatment.

To further investigate the large percentage of overall pavement condition ratings unaffected by treatment, the effects of the treatment on condition were grouped based on the overall condition of the pavement before the treatment. Table 25 presents the results of this investigation and shows that the largest percentage of the "no change" is a result of a before condition of fair and, to a lesser degree, a before condition of good. Again, this is not unexpected, as the majority of survey groupings are classified as fair as illustrated by the example of how the overall pavement condition rating can be unaffected by treatment as a result of the rating being a combination of two or three metrics.

Although the previous analysis showed that not all pavement test section conditions will be affected by all treatments, it is important that the performance measure be affected by M&R activities. The performance measures are the percentage of pavements on the IHS and NHS (excluding interstate) in good condition and the percentage of pavements on the IHS and NHS (excluding interstates) in poor condition. The performance measures look at the percentage for the entire network, or in this case, entire groupings of sections, and are not broken down by treatment type as just presented.

Table 25. Percentage change based on before-treatment condition.

Before M&R Condition	Pavement Type	No Change (%)	Improve (%)	Reduce (%)
Good	AC-all	10	0	90
Good	AC-fatigue	52	0	48
Good	JPCC	65	0	35
Good	CRCP	86	0	14
Fair	AC-all	87	5	8
Fair	AC-fatigue	88	5	7
Fair	JPCC	88	4	7
Fair	CRCP	64	33	3
Poor	AC-all	0	100	0
Poor	AC-fatigue	25	75	0
Poor	JPCC	91	9	0
Poor	CRCP	N/A	N/A	N/A

N/A = not applicable.

Table 26 shows the comparison for the LTPP test section–derived performance measures before treatment and after treatment to illustrate the impact of M&R activities. For AC-all, AC-fatigue, and CRCPs, the percent good increases as a result of the M&R activities. For AC-all and AC-fatigue, the percentage poor reduces as a result of M&R activities. The percentage poor for CRCP increases as a result of M&R activities. This is likely a result of there being few pavements in poor condition as well as the fact that patching, which is considered an M&R activity, does in fact increase the percent of cracking for CRCPs and therefore could have a negative impact on the defined overall condition and hence cause the percent poor to increase. The performance measures for JPCC do not follow the expected trend as the other pavement types. The percentage of good slightly decreases, while the percentage of poor slightly increases. As discussed previously, only grinding was shown to improve the overall pavement condition rating of JPCC pavements, and that was minimal in comparison to the amounts associated with other treatments. Therefore, the performance measures for JPCC pavements do not show the impact of M&R activities. However, the performance measures for AC and CRCPs are affected by M&R activities.

Table 26. Effect of treatments on performance measures.

Pavement Type	Before Good (%)	Before Poor (%)	After Good (%)	After Poor (%)
AC-all	3.6	2.2	6.1	1.4
AC-fatigue	6.2	1.2	11.1	1.0
JPCC	4.2	2.5	4.0	3.0
CRCP	9.5	0	13.8	0.5

REVIEW OF CONDITION RATINGS AGAINST THRESHOLDS

The last performance measure validation analysis entailed the review of the overall pavement condition rating against thresholds. As part of this analysis, the following three characteristics of the overall pavement condition rating were considered:

- Composition of overall condition rating compared to metric condition.
- Number of metrics in a given condition that make up overall condition rating.
- Average time for condition rating to change.

The initial analysis of these three characteristics and their impact on the overall pavement condition rating are detailed next. In addition, more indepth analyses of the three characteristics are presented in chapter 5.

Metric Drivers

The metric driver analysis compared the composition of the overall pavement condition rating to the metric conditions—that is to say, how the overall condition rating was affected by the individual condition metrics, which can indicate if there is a specific metric or metrics that are driving the overall pavement condition rating. Table 27 and table 28 show the breakdown of the individual metrics for AC-all and AC-fatigue pavements, respectively. Cracking appears to be the driver for the overall pavement condition rating being fair for the AC-all pavements, as 75 percent of the overall condition rating at fair have cracking in either fair or poor condition. However, the overall pavement condition rating for being fair for AC-fatigue pavements is driven by rutting, with 75 percent of the overall condition rating at fair having rutting in either fair or poor condition. The overall pavement condition rating being poor for AC pavements is driven by cracking and rutting.

Table 27. AC-all percentage metrics.

Performance Measure	IRI G (%)	IRI F (%)	IRI P (%)	Cracking G (%)	Cracking F (%)	Cracking P (%)	Rutting G (%)	Rutting F (%)	Rutting P (%)
Good (G)	100	0	0	100	0	0	100	0	0
Fair (F)	73	26	1	24	18	57	41	55	4
Poor (P)	22	27	51	2	1	97	10	33	58

Table 28. AC-fatigue percentage metrics.

Performance Measure	IRI G (%)	IRI F (%)	IRI P (%)	Cracking G (%)	Cracking F (%)	Cracking P (%)	Rutting G (%)	Rutting F (%)	Rutting P (%)
Good (G)	100	0	0	100	0	0	100	0	0
Fair (F)	65	32	2	56	15	29	25	68	7
Poor (P)	19	2	52	7	1	91	8	30	62

Table 29 shows the breakdown of individual metrics for JPCC pavements. As shown, IRI may have a larger impact on the overall pavement condition rating being fair than the other two metrics—when IRI is in fair or poor condition, the overall condition rating is fair 73 percent of the time. As also shown in table 29, IRI and cracking appear to drive the overall poor condition rating, more so than faulting, as it takes two metrics to drive the poor condition.

Table 29. JPCC percentage metrics.

Performance Measure	IRI G (%)	IRI F (%)	IRI P (%)	Cracking G (%)	Cracking F (%)	Cracking P (%)	Faulting G (%)	Faulting F (%)	Faulting P (%)
Good (G)	100	0	0	100	0	0	100	0	0
Fair (F)	27	70	3	58	10	31	52	48	1
Poor (P)	0	16	84	9	9	88	13	33	54

The breakdown of the individual metrics for CRCPs is shown in table 30. This table clearly shows that IRI is the driver for the overall pavement condition rating—when IRI is in fair condition, the overall pavement condition rating is fair 93 percent of the time. With the low amount of cracking on CRCP LTPP pavements (average of 1.2 percent), it is expected that IRI would be the driver.

Table 30. CRCP percentage metrics.

Performance Measure	IRI G (%)	IRI F (%)	IRI P (%)	Cracking G (%)	Cracking F (%)	Cracking P (%)
Good (G)	100	0	0	100	0	0
Fair (F)	7	93	0	88	7	5
Poor (P)	0	0	100	0	0	100

As part of the driver analysis, a review was also conducted to identify the number of metrics in a given condition (good, fair, or poor) that make up that overall pavement condition rating. Since all metrics are required to be good for the overall pavement condition rating to be good, this was not considered in the analysis. In addition, in the case of CRCP, both metrics need to be poor for the overall condition rating to be poor; therefore, CRCPs were not included in this analysis.

The number of metrics for each pavement type and condition rating are presented in table 31. As shown, the overall pavement condition rating of fair was largely affected by one metric or less in fair condition, as illustrated by the high percent (more than 64 percent) of either zero or one metric being in fair condition. This could occur if two metrics are good and one metric is fair or poor or one metric is each good, fair, and poor. Table 31 also shows that the overall condition rating of poor is largely a result of two metrics being poor, and not all three. These findings also support the previous findings of the overall pavement condition rating not being affected as much by M&R activities, as it shows that it does not require many metrics to be classified as fair for the overall pavement condition to be fair.

Table 31. Number of metrics by condition.

Pavement Type	Cracking Type	Condition Rating	0 Metrics (%)	1 Metric (%)	2 Metrics (%)	3 Metrics (%)
AC	All	Fair	25	52	22	1
AC	All	Poor	0	0	94	6
AC	Fatigue	Fair	12	63	22	3
AC	Fatigue	Poor	0	0	94	6
JPCC	JPCC	Fair	10	54	34	2
JPCC	JPCC	Poor	0	0	74	26

Temporal Condition Changes

The third and last of the threshold analyses focused on the LTPP Seasonal Monitoring Program (SMP) test sections. The SMP study was designed to measure the impact of daily, seasonal, and yearly temperature and moisture changes on pavement structures and the response to loads. Because of this, these test sections had more than one condition survey performed annually; however, the analysis only considered section groupings within a single construction event. As such, they offer a good sample to analyze the average time for the overall pavement condition rating to change over time. However, because CRCP test sections were not included in the SMP, other LTPP CRCP test sections that had at least four survey groupings within a construction event were used in this analysis.

Table 32 provides a summary of the number of survey groupings and results from the analysis in question. As shown, the average timespan of all survey groupings identifies the average length of time between the first survey grouping for a section to the last survey grouping of a section, which was 5.0, 5.8, 7.6, and 16.2 yr for AC-all, AC-fatigue, JPCC, and CRCP, respectively. The data were then reviewed to determine the time it took for the condition to change from the initial condition. The analysis showed that the overall pavement condition was largely static, as the condition remained constant from the first to last survey grouping for more than 60 percent of the sections for all pavement types. For the survey groupings where the condition remained constant, the average timespan is provided. For those survey groupings where the condition did not remain constant, the average time required for the condition to change was calculated. This analysis again shows how static the condition is, as the average time to change the condition was at least 4.2 yr for the AC-all.

The implications of the results presented in table 32 are that the pavement condition ratings are stable over time. Although the pavement condition ratings and performance measures are affected by some M&Rs, as presented previously, it is important that repairs are strategic in nature to make the desired impact on the performance measure. In addition, the findings presented in the table suggest that data collection on an annual basis may not be required to capture changes in the pavement condition ratings and performance measures.

Table 32. Summary of temporal analysis.

Pavement Type	AC-All	AC-Fatigue	JPCC	CRCP
Number of survey groupings	130	98	27	37
Average timespan of all survey groupings	5.0 yr	5.8 yr	7.6 yr	16.2 yr
Percent of survey groupings remaining constant	67%	62%	63%	84%
Average timespan constant	3.8 yr	4.0 yr	5.5 yr	15.8 yr
Average time to change	4.2 yr	4.5 yr	4.5 yr	12.0 yr

CHAPTER 5. OTHER PERFORMANCE MEASURE CONSIDERATIONS: THRESHOLDS, TEMPORAL CHANGES, AND DRIVERS

Based on the findings presented in chapter 4, the following three analyses were undertaken by the project team:

- Threshold analysis.
- Temporal analysis of IHS LTPP test sections.
- Performance measure drivers.

The approach to and findings from each of the above analyses are detailed next.

THRESHOLD ANALYSIS

The objective of this analysis was to consider alternate pavement condition threshold values to those proposed by FHWA in the NPRM. Alternate threshold values were provided to the project team by the FHWA for IRI, cracking, and faulting—these alternate thresholds correspond with those in the Final Rule, which had not yet been issued at the time of the analyses presented in this chapter. The alternate threshold values were first used to evaluate the condition in terms of good, fair, and poor for each of the pavement condition metrics. The resulting condition metrics were then combined to form the overall pavement condition rating. To combine the individual condition metrics into one overall pavement condition rating, the survey groupings detailed in the previous chapter were used. These survey groupings required that each of the individual metric measurements was taken within 1 yr of the others.

The alternate threshold values are presented in table 33 along with the NPRM threshold values. The alternate threshold values that differ from the NPRM values are the poor threshold for roughness for areas with populations of at least 1,000,000, the poor threshold for percent cracking for AC and JPCC pavements, and the faulting threshold for good for JPCC pavements.

Table 33. NPRM and alternate threshold values.

Condition Metric	Performance Level	NPRM Threshold	Alternate Threshold
IRI	Good	<95	<95
IRI	Poor	>170: areas with a population less than 1,000,000 >220: areas with a population of at least 1,000,000	>170
Percent cracking, AC	Good	<5%	<5%
Percent cracking, AC	Poor	>10%	>20%
Percent cracking, JPCC	Good	<5%	<5%
Percent cracking, JPCC	Poor	>10%	>15%
Faulting	Good	<0.05	<0.10
Faulting	Poor	>0.15	>0.15

The overall pavement condition rating was formulated in the following three different ways for AC pavements:

- Using the alternate roughness threshold.
- Using the alternate cracking threshold.
- Using both the alternate roughness and cracking thresholds.

The overall pavement condition rating was formulated in the following four different ways for JPCC pavements:

- Using the alternate roughness threshold.
- Using the alternate cracking threshold.
- Using the alternate faulting threshold.
- Using all of the alternate thresholds.

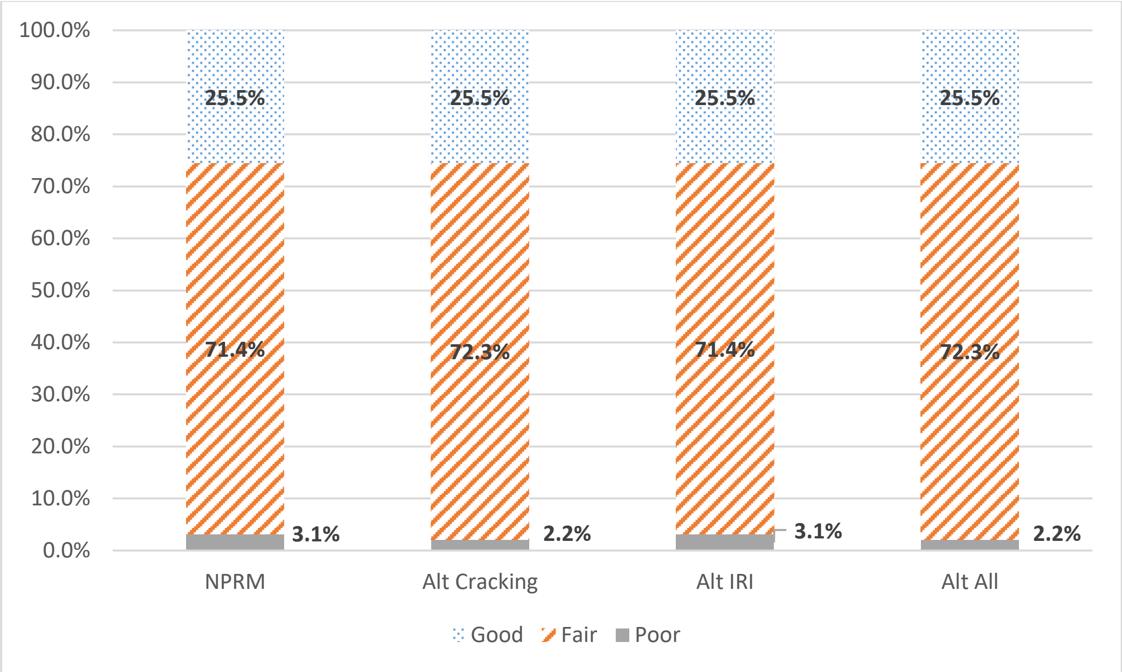
The overall pavement condition rating for CRCP was only affected by the alternate roughness threshold and therefore was only formulated one time. Once the overall pavement condition ratings were calculated using the alternate thresholds, these were compared to the pavement condition ratings computed using the threshold values as stipulated in the NPRM.

Table 34 presents the comparison of AC-all and AC-fatigue cracking metrics. As shown, the alternate threshold values reduce the percent poor by 20.7 percent (i.e., from 42.5 to 21.8 percent) and 8.2 percent (i.e., from 17.9 to 9.7 percent) for AC-all and AC-fatigue, respectively. The effect of the alternate threshold on pavements is larger for AC-all because less cracking is included in AC-fatigue calculation. Table 34 also shows that there is no difference in the percentage of fair and poor for both AC-all and AC-fatigue between the NPRM and alternate roughness thresholds. This is because, although there were test sections in the comparison that were located in areas with populations greater than 1,000,000, none of them had an IRI greater than 170 inch/mi (i.e., alternate threshold), and therefore no test sections were affected.

Table 34. AC metric comparison.

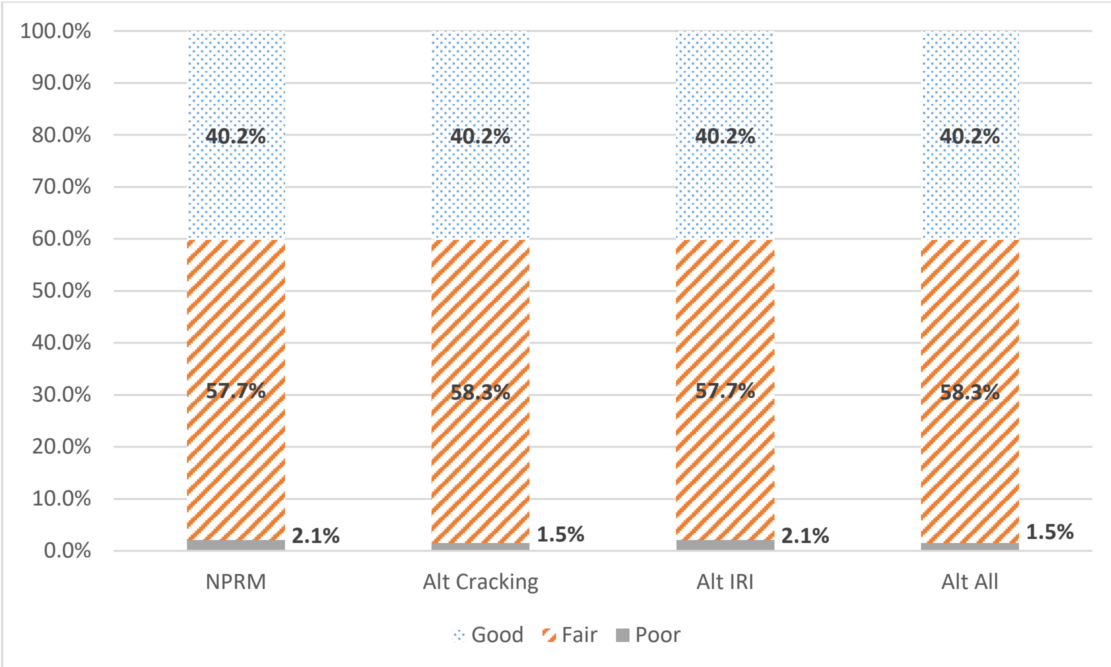
Pavement Type	Metric	NPRM Good (%)	NPRM Fair (%)	NPRM Poor (%)	Alternate Good (%)	Alternate Fair (%)	Alternate Poor (%)
AC-all	Percent cracking	44.1	13.4	42.5	44.1	34.1	21.8
AC-all	IRI	82.2	16.1	1.7	82.2	16.1	1.7
AC-fatigue	Percent cracking	73.6	8.5	17.9	73.6	16.7	9.7
AC-fatigue	IRI	82.2	16.1	1.7	82.2	16.1	1.7

Figure 10 and figure 11 compare the results of the overall condition ratings as estimated using the three AC pavement formulations and the NPRM thresholds. As shown, even though the alternate cracking threshold resulted in a 20.7-and 8.2-percent reduction at the metric level in percent poor for AC-all and AC-fatigue, respectively, the change in threshold value has a minimal effect on the overall condition. The overall condition percent poor was reduced by 0.9 and 0.6 percent for AC-all and AC-fatigue, respectively. The overall condition computed using both alternate thresholds reflects this same minimal change. In terms of IRI, since the alternate threshold had no effect at the metric level, there is no change in overall condition between the NPRM and alternate IRI threshold.



Source: FHWA.

Figure 10. Bar graph. Overall condition comparison for AC-all.



Source: FHWA.

Figure 11. Bar graph. Overall condition comparison for AC-fatigue.

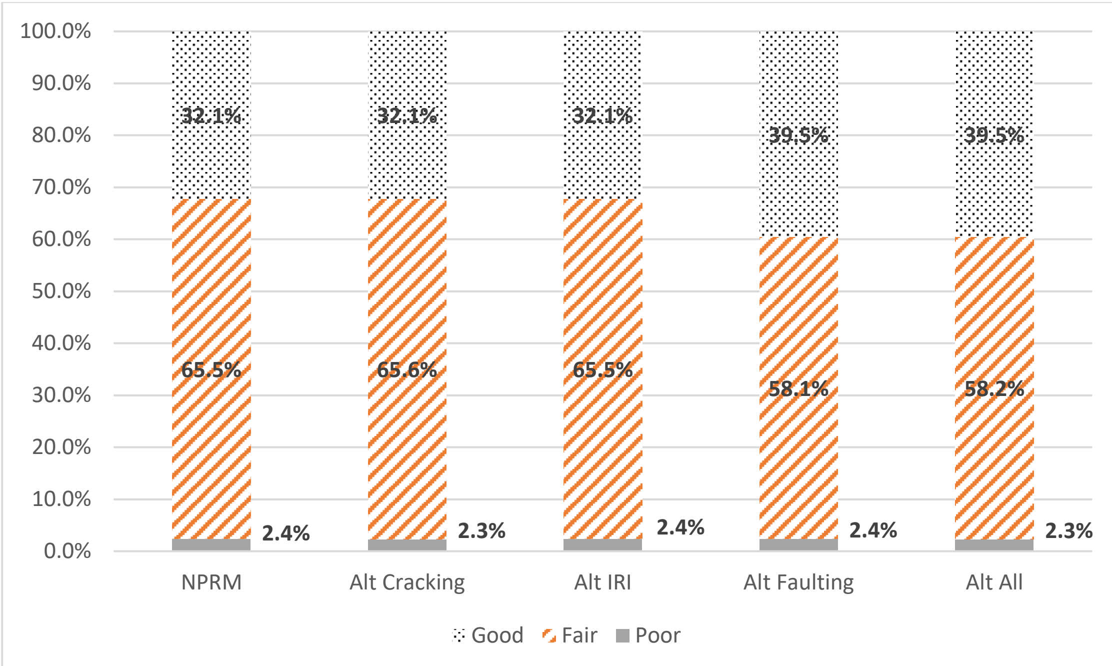
Table 35 presents the comparison for the metrics associated with the JPCC and CRCP test sections. As shown, the alternate cracking threshold reduces the percent poor by 2.4 percent (i.e., from 18.6 to 16.2 percent) for JPCC, while there is no change in percent poor for JPCC as a result of the alternate IRI threshold. On the other hand, the alternate faulting threshold increases the percent good by 20.9 percent (i.e., from 69.1 to 90.0 percent). For CRCP, the only alternate threshold is for IRI, which increases the percent poor by 0.8 percent (i.e., from 1.6 to 2.4 percent).

Table 35. JPCC and CRCP metric comparison.

Pavement Type	Metric	NPRM Good (%)	NPRM Fair (%)	NPRM Poor (%)	Alternate Good (%)	Alternate Fair (%)	Alternate Poor (%)
JPCC	Percent cracking	74.7	6.7	18.6	74.7	9.1	16.2
JPCC	IRI	50.9	45.8	3.3	50.9	45.8	3.3
JPCC	Faulting	69.1	28.8	2.1	90.0	7.9	2.1
CRCP	IRI	56.3	42.1	1.6	56.3	41.3	2.4

Figure 12 presents the overall condition comparison results based on the three formulations described previously for JPCC pavements and the NPRM thresholds. As shown, using the alternate cracking threshold reduces the percent poor for the overall condition by 0.1 percent (from 2.4 to 2.3 percent). Since there was no effect at the metric level in using the alternate roughness threshold, there is no change in overall condition between the NPRM and alternate IRI threshold. The largest effect on overall condition is a result of the alternate faulting threshold, which increases percent good by 7.4 percent (from 32.1 to 39.5 percent) for the overall condition.

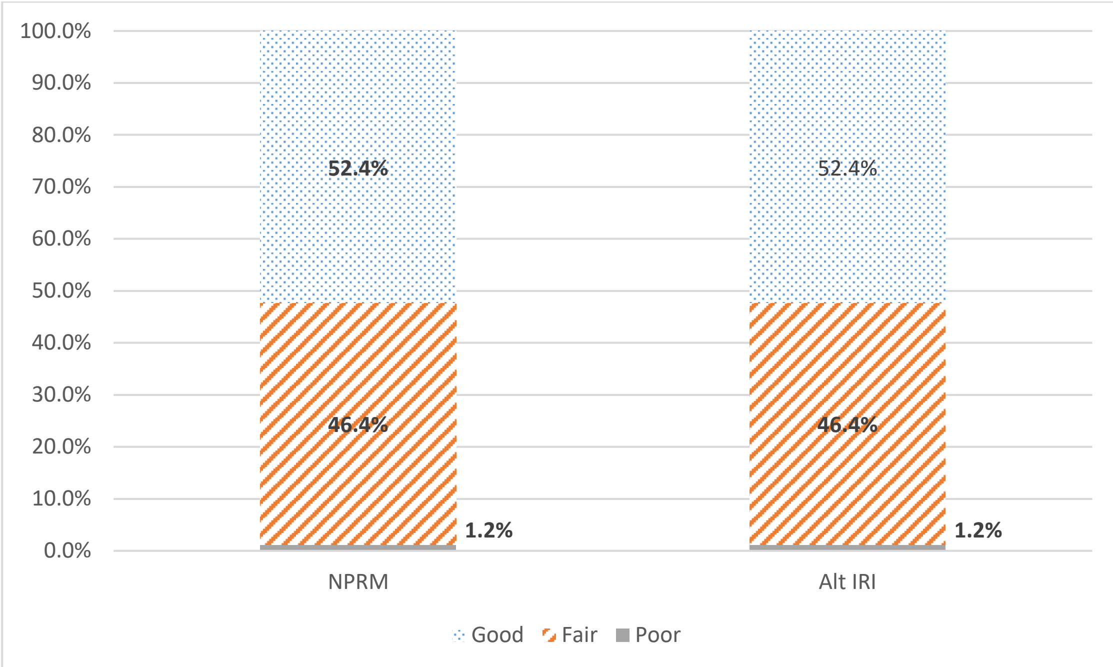
The overall condition computed using all three alternate thresholds reflects the referenced effects: Percent poor decreases by 0.1 percent (from 2.4 to 2.3 percent), and percent good increases by 7.4 percent (from 32.1 to 39.5 percent).



Source: FHWA.

Figure 12. Bar graph. Overall condition comparison for JPCC.

Figure 13 presents the overall condition comparison results based on the alternate IRI threshold for CRCP and the NPRM thresholds. There was a small change in the percentage of poor at the metric level for IRI and, subsequently, no change to the overall condition for CRCP in this study.



Source: FHWA.

Figure 13. Bar graph. Overall condition comparison for CRCP.

The analysis in question also considered how the alternate threshold values affected the performance measures. Table 36 summarizes the change in performance measures resulting from the alternate thresholds relative to the NPRM thresholds. The values shown in this table were determined using the overall conditions presented in figure 10 through figure 13. The results show very little effect on the performance measure with the exception of the faulting threshold, which improves the percent good by 7.4 percent (from 32.1 to 39.4 percent).

Table 36. Improvement in performance measures as a function of alternate thresholds.

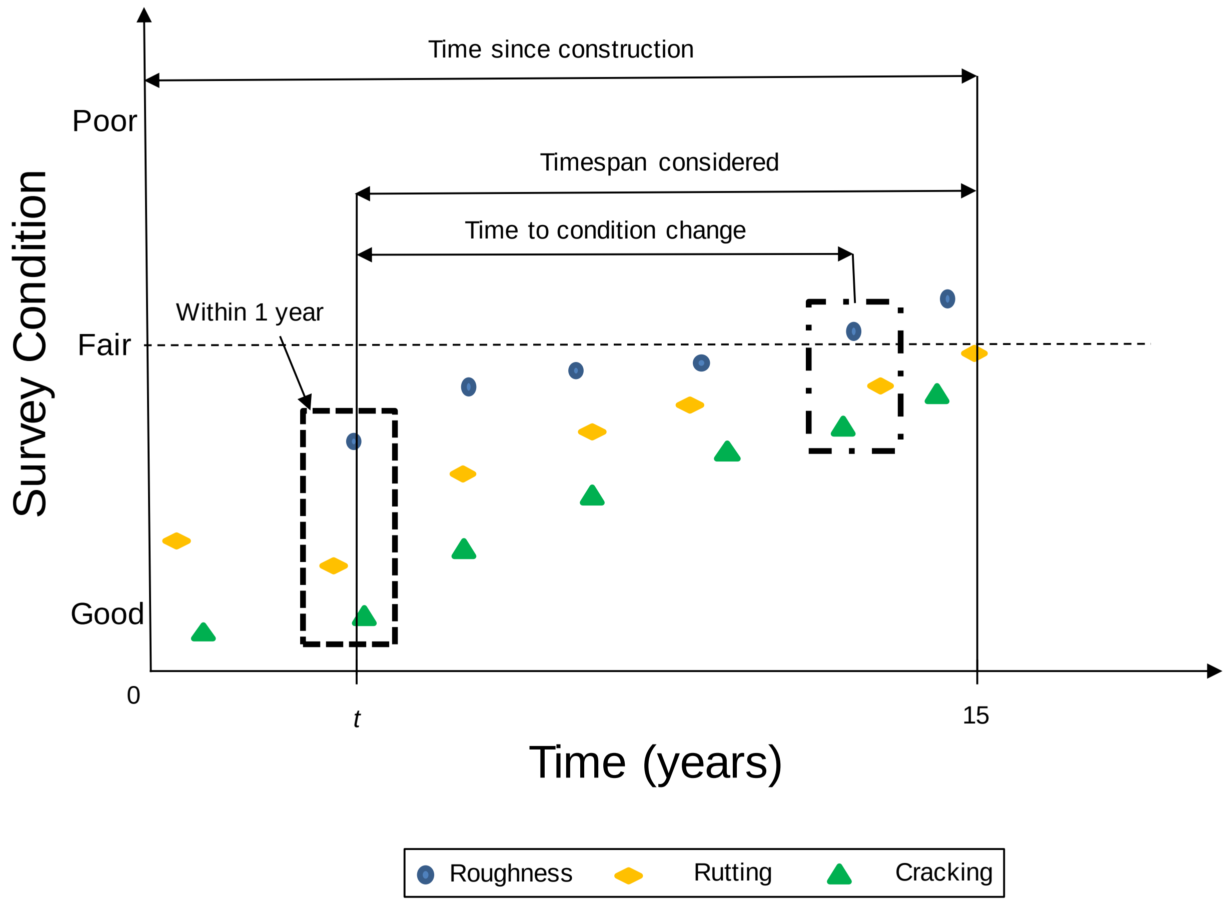
Pavement Type	Threshold Type	% Good	% Poor
AC-all	IRI	0	0
AC-all	Cracking	0	–0.9
AC-all	Overall	0	–0.9
AC-fatigue	IRI	0	0
AC-fatigue	Cracking	0	–0.6
AC-fatigue	Overall	0	–0.6
JPCC	IRI	0	0
JPCC	Cracking	0	–0.1
JPCC	Faulting	+7.4	0
JPCC	Overall	+7.4	–0.1
CRCP	IRI	0	–0.8
CRCP	Overall	0	0
Network	Overall	+2.3	–0.4

In conclusion, the analysis findings show that the alternate thresholds have some effect on a few of the pavement metrics, but less of an effect on the overall condition and performance measures. The only exception is the alternate faulting threshold, which has a large effect on the pavement metric, overall condition, and performance measure. The result on the network of all pavement sections considered shows an increase of 2.3 percent good and a decrease of 0.4 percent poor.

TEMPORAL ANALYSIS OF IHS LTPP TEST SECTIONS

Previously, as presented in chapter 4, a temporal analysis was conducted using LTPP SMP AC and JPCC test sections as well as selected LTPP CRCP test sections. In this section, LTPP test sections located on the IHS were used to further analyze temporal effects on pavement condition metrics and overall condition ratings and hence performance measures.

Figure 14 depicts the various timespans referenced in this analysis and the meaning of each. As stated earlier, a survey grouping was only formed provided that each of the individual metric measurements was taken within 1 yr of the others. As a result, many times, there were surveys between the time of last construction (as designated by time equal to zero in figure 14) and the first grouping considered in the analysis. This often created a time lag between the time of construction and the time the first grouping was considered. Figure 14 shows the time the first grouping was considered as time "*t*," which changes for each pavement section. This time between construction and first survey grouping considered in this analysis was on average 1.5 yr for AC pavements, which is a conservative estimate for JPCC pavements and CRCP. Although this time was calculated by only considering test sections that had a first grouping in good condition, this time between construction and first grouping should not be added to the timespan considered, since the actual condition at construction is not known, but was assumed to be good over the timespan.



Source: FHWA.

Figure 14. Graph. Temporal groupings.

The timespan considered under this analysis was from the time of the first survey grouping to the time of the last survey grouping, which in figure 14 is shown to be (15 – *t*) yr. The analysis presented in chapter 4 showed that the average timespan from the first survey grouping to the last survey grouping was 5.0, 5.8, 7.6, and 16.2 yr for AC-all, AC-fatigue, JPCC, and CRCP, respectively.

The time to change was calculated as the time between the first survey grouping and the first grouping of a different condition. For example, in figure 14, the first grouping is in good condition, while the fifth grouping is in fair condition, since the roughness survey is beyond the fair threshold. Therefore, the time between the first survey grouping and the fifth survey grouping is identified as the time to change the overall condition. For sections where the condition did not remain constant, the average time required for the overall condition to change was 4.2 yr for AC-all, 4.5 yr for AC-fatigue, 4.5 yr for JPCC, and 12.0 yr for CRCPs for the analysis presented in chapter 4. This calculation is for a change in overall condition regardless of starting condition. Because these timespans do not consider the time from construction to the first survey grouping, they are conservative.

As stated earlier, the objective of the analysis in question was to perform similar temporal analyses to those conducted using the LTPP SMP test sections but using LTPP test sections on the IHS. To accomplish this, a list of LTPP test sections on the IHS was first generated. These test sections were to have had at least three survey groupings within a construction event. The pavement condition metrics and overall pavement condition ratings were then computed for these test sections using the alternate thresholds discussed in the previous section. Unlike the temporal analysis on the LTPP SMP test sections, the temporal analysis in question differentiated the time to change from good to fair, fair to poor, and when the overall condition remained good, fair, or poor over the entire analysis period.

Table 37 provides the analysis results, showing both the number of test sections within each condition and the average time to change—the average time is presented for each grouping. For conditions that remained constant, the average time represents the timespan considered as depicted in figure 14, while for conditions that changed (i.e., good to fair), the average time represents the average time to change condition as depicted in figure 14. For example, there were 180 test sections that remained fair (i.e., did not change) for an average span of 5.8 yr for AC-all. The total timespan listed in the bottom row of the table is the average number of years that each survey grouping, independent of condition, had data available for the analysis (i.e., the timespan considered as depicted in figure 14 for all sections). The smallest average time to change was 4.0 yr for AC-all to change from good to fair and from fair to poor, while the largest average timespan occurred on CRCP, where the condition remained fair for 11.5 yr. The percentage of test sections that remained constant over the entire analysis period ranged from 51 percent for AC-all to 86 percent for CRCP. This analysis again shows that the pavement condition is largely static. In addition, there are few test sections (less than 1 percent) that remained in poor condition for extended periods of time. The average time that those test sections remained poor is also less than the average time sections of the same pavement type remained in good or fair condition. Since the analysis only considered pavements with at least three groupings between treatments, it implies that pavements that became poor likely received treatment to improve their condition.

Table 37. Average time to change for sections on the IHS.

Condition	AC-All Number of Sections	AC-All Average Time (Years)	AC-Fatigue Number of Sections	AC-Fatigue Average Time (Years)	JPCC Number of Sections	JPCC Average Time (Years)	CRCP Number of Sections	CRCP Average Time (Years)
Good, constant	24	5.2	115	6.3	19	7.9	18	11.3
Fair, constant	180	5.8	130	5.5	103	7.7	12	11.5
Poor, constant	2	5.5	1	4.7	3	7.3	0	N/A
Good to fair	188	4.0	135	4.8	45	6.7	5	8.5
Fair to poor	12	4.0	9	4.4	15	6.3	0	N/A
Total number of sections and span of time	406	6.4	390	6.3	185	9.0	35	11.7

The implications of the results presented in table 37 are that the pavement condition ratings are stable; they do not change rapidly. Although the pavement condition ratings and performance measures are affected by some M&R treatments, as detailed in chapter 4, it is important that repairs are strategic in nature to have the desired effect on the performance measure. This element is a critical element of the guidelines developed under this project, as detailed in chapter 6. In addition, the findings presented in the table suggest that data collection on an annual basis may not be required to capture changes in the pavement condition ratings and performance measures.

To investigate whether there were differences in these timespans between factors such as climate zone and urban versus rural, analyses of variance (ANOVAs) were conducted. Table 38 through table 41 present the results of the ANOVAs for AC-all, AC-fatigue, JPCC, and CRCP, respectively. The factors compared included climate zone comparisons and urban versus rural. The tables present the means and standard deviation for each factor and whether the difference between the factors in each group is statistically significant. The results show that freeze areas have the lowest average time to change. The dry-freeze climate zone had the lowest average time to change for both AC-all and CRCP, while the wet-freeze climate zone had the lowest average time to change for JPCC. The only statistically significant difference between urban and rural was for JPCC pavements, where the rural sections had a lower average time to change compared to the urban sections.

Table 38. ANOVA results for AC-all.

Group	Factors	Mean (Years)	Standard Deviation (Years)	Statistically Significant?
1	Wet-freeze	5.02	9.96	No
1	Wet-no-freeze	5.80	7.34	No
2	Dry-freeze	4.37	4.52	No
2	Dry-no-freeze	4.97	10.71	No
3	Dry-freeze	4.37	4.52	No
3	Wet-freeze	5.02	9.96	No
4	Wet-no-freeze	5.80	7.34	No
4	Dry-no-freeze	4.97	10.71	No
5	Urban	4.90	5.66	No
5	Rural	4.84	8.69	No

Table 39. ANOVA results for AC-fatigue.

Group	Factors	Mean (Years)	Standard Deviation (Years)	Statistically Significant?
1	Wet-freeze	5.37	7.89	No
1	Wet-no-freeze	5.82	7.55	No
2	Dry-freeze	4.73	5.06	Yes
2	Dry-no-freeze	5.89	14.93	Yes
3	Wet-no-freeze	5.82	7.55	No
3	Dry-no-freeze	5.89	14.93	No
4	Dry-freeze	4.73	5.06	Yes
4	Wet-freeze	5.37	7.89	Yes
5	Urban	5.70	5.79	No
5	Rural	5.33	9.23	No

Table 40. ANOVA results for JPCC.

Group	Factors	Mean (Years)	Standard Deviation (Years)	Statistically Significant?
1	Wet-freeze	5.28	8.86	Yes
1	Wet-no-freeze	12.93	35.08	Yes
2	Dry-freeze	7.10	20.23	No
2	Dry-no-freeze	8.11	26.59	No
3	Dry-freeze	7.10	20.23	Yes
3	Wet-freeze	5.28	8.86	Yes
4	Wet-no-freeze	12.93	35.08	Yes
4	Dry-no-freeze	8.11	26.59	Yes
5	Urban	10.17	20.17	Yes
5	Rural	6.69	20.03	Yes

Table 41. ANOVA results for CRCP.

Group	Factors	Mean (Years)	Standard Deviation (Years)	Statistically Significant?
1	Wet-freeze	18.42	23.71	No
1	Wet-no-freeze	11.47	35.55	No
2	Dry-freeze	9.25	24.90	No
2	Dry-no-freeze	10.78	55.64	No
3	Dry-freeze	9.25	24.90	Yes
3	Wet-freeze	18.42	23.71	Yes
4	Wet-no-freeze	11.47	35.55	No
4	Dry-no-freeze	10.78	55.64	No
5	Urban	15.01	64.82	No
5	Rural	10.03	28.37	No

Some of these results may appear to be counterintuitive. For example, the average timespan for JPCC in the wet-no-freeze zone is 12.93 yr, which is longer than the 8.11-yr average timespan for JPCC in the dry-no-freeze zone. However, further review of these datasets reveals that the wet-no-freeze zone includes 9 test sections in comparison to the 46 test sections in the dry-no-freeze zone. Similar differences are observed for the AC test sections, with 11 test sections in the wet-no-freeze zone and 113 test sections in the dry-no-freeze zone. These differences in the number of test sections likely produce biases in the results.

PERFORMANCE MEASURE DRIVERS

In chapter 4, the overall pavement conditions were investigated to show how the overall condition was affected by the individual condition metrics. Each metric composition for the overall condition was presented, but the analysis did not consider how the metrics were combined to result in the overall condition. For each overall condition, the percentage that each metric was good, fair, or poor was presented. For example, if the overall condition was fair, condition of the IRI metric was 65 percent good, 32 percent fair, and 2 percent poor for AC-fatigue. Similar compositions were presented for rutting and cracking. In addition, the number of metrics for a given condition that made up that overall pavement condition rating was investigated. The results showed that the overall pavement condition rating of fair was largely affected by one metric or less in fair condition (greater than 64 percent). This could occur if two metrics are good and one metric is fair or poor or one metric is each good, fair, and poor. Although the findings from these analyses were used to indicate if there was a specific metric that was driving the overall condition, there was not enough detail to fully understand the effects of the metrics on the overall condition.

In light of the above, the objective of the analysis presented in this section was to investigate in greater detail which metrics drive the overall condition and performance measures for both fair and poor condition using the alternate thresholds. It was anticipated that the results from this analysis would provide valuable input for use in the development of the guidelines presented in chapter 6, and this turned out to be the case.

The analyses presented in this section considered all the metric combinations that could result in the overall condition and differentiated between these metric combinations. This is important because different metric combinations require different treatments to have an effect on the overall condition. For example, take two pavement sections that have an overall condition of fair. The metrics that make up that overall condition are good, good, fair for one, and fair, fair, poor for the second. Although both pavement sections have the same overall condition, the individual condition metrics are not the same. The first pavement section could be improved to good condition by treating the metric that is in fair condition. Conversely, the second pavement section could deteriorate to poor condition if one or both of the two fair metrics drop to poor. Understanding which metrics drive the overall pavement condition was critical to the development of the guidelines presented in chapter 6, especially for the following “borderline” conditions:

- Fair:
    - Good, good, fair.
    - Fair, fair, poor.

- Poor:
    - Good, poor, poor.
    - Fair, poor, poor.

In addition, the following combinations of metrics were also investigated under this analysis:

- Fair:
    - Good, good, poor.
    - Good, fair, poor.
    - Good, fair, fair.

AC Pavement Drivers

Like the temporal analyses presented in the previous section, the metric driver analyses explored various factors, including climate zone (wet-freeze, wet-no-freeze, dry-freeze, and dry-no-freeze) and route type (interstate, U.S. route, and State route). Table 42 through table 44 present the drivers for AC-all. Table 42 presents the drivers for fair condition when only one of three metrics is causing the overall pavement condition to be fair. The good, good, poor (G-G-P) and the good, good, fair (G-G-F) groupings represent 25 and 26 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- Cracking is the driving metric for the G-G-P grouping.
- Rutting is the driving metric for the G-G-F grouping.
- Roughness is rarely the driver of either of these groupings.
- Rutting is shown to have a larger influence in the wet-no-freeze zone than other climate zones, representing 42 and 79 percent for the G-G-P and G-G-F groupings, respectively.

Table 42. AC-all fair driver—single metric.

Overall Condition	Metrics	Rutting (%)	Roughness (%)	Cracking (%)	Number of Groupings
Fair	G-G-P	8	1	91	1,649
Fair	G-G-F	63	6	30	1,708

Table 43 presents the drivers for fair condition when two of three metrics are not in good condition and they are contributing to the overall pavement condition of fair. The good, fair, poor (G-F-P), good, fair, fair (G-F-F), and fair, fair, poor (F-F-P) groupings represent 26, 10, and 11 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- The two driving metrics are most often cracking and rutting for the G-F-P and G-F-F groupings.
- The F-F-P groupings are mostly driven by rutting and roughness, which implies that cracking is mostly in the poor condition.

- Roughness and cracking, representing 23 percent, have a larger influence on State routes for the G-F-F groupings.

Although the overall condition of the F-F-P grouping is fair, if one of the two metrics that are fair degrades to poor condition, the overall pavement condition is also degraded to poor. Therefore, for this borderline grouping, the focus should be on the two drivers that are currently in fair condition to prevent the associated metrics and overall pavement condition from becoming poor. Accordingly, treatments that can improve rutting and roughness were considered in the development of the guidelines discussed in chapter 6.

Table 43. AC-all fair drivers—two metrics.

Overall Condition	Metrics	Rutting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Rutting (%)	Number of Groupings (%)
Fair	G-F-P	4	28	68	1,689
Fair	G-F-F	28	9	64	675
Fair	F-F-P	94	5	2	755

For the overall condition of AC pavements to be poor, at least two metrics must be in poor condition. Table 44 presents the driving metrics when two of three metrics are in poor condition resulting in the overall pavement condition of poor. The good, poor, poor (G-P-P) and fair, poor, poor (F-P-P) groupings represent 94 percent of the total number of groupings in poor condition, while 6 percent of the total number of groupings are a result of all three metrics being in poor condition. The table shows the following:

- The two main drivers are cracking and rutting for all climate zones with the exception of dry-freeze as well as for State routes where roughness and cracking are the main drivers, representing 68 and 55 percent, respectively.

- Cracking is poor most often, with more than 90 percent of the groupings in these tables including the cracking metric (i.e., by adding the roughness/cracking and cracking/rutting), while the division between roughness and rutting is almost equal with the exception of the wet-no-freeze zone where rutting is higher with 80 percent.

- To improve the overall condition to fair, only one of the metrics for the groupings shown in the table needs to be improved. These groupings were considered in the development of the guidelines detailed in chapter 6.

Table 44. AC-all poor drivers.

Overall Condition	Metrics	Rutting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Rutting (%)	Number of Groupings
Poor	G-P-P/ F-P-P	3	45	52	418

Table 45 through table 47 present the drivers for AC-fatigue. Table 45 presents the drivers for fair condition when only one of three metrics is causing the overall pavement condition to be fair. The G-G-P and the G-G-F groupings represent 12 and 45 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- Cracking is the driving metric for the G-G-P grouping.
- Rutting is the driving metric for the G-G-F grouping.
- Roughness is rarely the driver of either the G-G-P or G-G-F groupings but is slightly more a driver for State routes with 14 and 24 percent, respectively.
- Rutting appears to have a larger influence in the wet-no-freeze zone than other climate zones and, as a result, is the driver of the G-G-P grouping, representing 64 percent as opposed to cracking.
- These results are fairly consistent with the AC-all results with slight differences between the AC-all and AC-fatigue due to AC-fatigue having lower percentage cracking, and therefore it is less of a driver.

Table 45. AC-fatigue fair driver—single metric.

Overall Condition	Metrics	Rutting (%)	Roughness (%)	Cracking (%)	Number of Groupings
Fair	G-G-P	29	4	67	652
Fair	G-G-F	75	14	11	2,413

Table 46 presents the drivers for fair condition when two of three metrics are not in good condition and to contribute to the overall pavement condition of fair. The G-F-P, G-F-F, and F-F-P groupings represent 18, 14, and 8 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- For the G-F-P grouping, the two driving metrics are most often cracking and rutting.
- The G-F-F and F-F-P groupings are driven mostly by rutting and roughness with the exception of the G-F-F in the wet-no-freeze zone, which is driven by cracking and rutting, representing 69 percent.
- There is a difference between the drivers for the G-F-F grouping between AC-all and AC-fatigue. Cracking and rutting are the drivers for the AC-all grouping, while rutting and roughness are the drivers for the AC-fatigue grouping. This can again be attributed to lower percentage of cracking included in AC-fatigue, and hence it is not as likely to be a driver.

Table 46. AC-fatigue fair drivers—two metrics.

Overall Condition	Metrics	Rutting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Rutting (%)	Number of Groupings (%)
Fair	G-F-P	19	23	58	956
Fair	G-F-F	60	8	32	765
Fair	F-F-P	90	5	5	416

Table 47 presents the driving metrics when two of three metrics are in poor condition resulting in the overall pavement condition of poor. The G-P-P and F-P-P groupings represent 94 percent of the total number of groupings in poor condition, while 6 percent of the groupings in poor condition are a result of all three metrics being poor. The table shows the following:

- The two main drivers are cracking and rutting for all climate zones with the exception of the dry-freeze zone where roughness and cracking are the main drivers, representing 66 percent.
- The two drivers for U.S. routes are cracking and rutting, representing 63 percent.
- The two drivers for interstate and State routes are roughness and cracking, representing 53 and 45 percent, respectively.

Table 47. AC-fatigue poor drivers.

Overall Condition	Metrics	Rutting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Rutting (%)	Number of Groupings
Poor	G-P-P/ F-P-P	9	40	51	265

JPCC Pavement Drivers

The drivers for JPCC pavements are presented in table 48 through table 50. Table 48 presents the drivers for fair condition when only one of three metrics is causing the overall pavement condition to be fair. The G-G-P and the G-G-F groupings represent 10 and 41 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- Cracking is the driving metric for the G-G-P grouping.
- Roughness is the driving metric for the G-G-F grouping.
- Faulting is rarely the driver of either of these groupings, but it is slightly more a driver for State routes for the G-G-F grouping, representing 35 percent.

- Roughness is more likely a factor in the wet-no-freeze zone, representing 50 percent for the G-G-P grouping.

- Faulting is more likely a factor in the dry-no-freeze zone, representing 43 percent for the G-G-F grouping.

Table 48. JPCC fair driver—single metric.

Overall Condition	Metrics	Faulting (%)	Roughness (%)	Cracking (%)	Number of Groupings
Fair	G-G-P	0	11	89	265
Fair	G-G-F	26	66	8	1,116

Table 49 presents the drivers for fair condition when two of three metrics are not in good condition contributing to the overall pavement condition of fair. The G-F-P, G-F-F, and F-F-P groupings represent 13, 22, and 12 percent of the total number of groupings in fair condition, respectively. The table shows the following:

- For the G-F-P grouping, the two driving metrics are most often roughness and cracking.
- The G-F-F and F-F-P groupings are driven mostly by faulting and roughness.

With faulting and roughness being the main drivers for the G-F-F and F-F-P groupings, the use of diamond grinding as a treatment to address these metrics and to prevent borderline F-F-P condition pavements from falling to poor condition seems appropriate. It is also possible that this treatment, if applied correctly, could improve the overall pavement condition to good. These drivers and treatment options were investigated further during development of the guidelines described in chapter 6.

Table 49. JPCC fair drivers—two metrics.

Overall Condition	Metrics	Faulting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Faulting (%)	Number of Groupings
Fair	G-F-P	16	66	18	366
Fair	G-F-F	79	15	6	614
Fair	F-F-P	96	1	3	321

The two of three metric drivers of the overall poor condition for JPCC pavements are presented in table 50. The G-P-P and F-P-P groupings represent 72 percent of the total number of groupings in poor condition. The table shows the following:

- The two main drivers are roughness and cracking, particularly on U.S. routes where this happens 85 percent of the time.

- Cracking and faulting have a greater influence in the wet-no-freeze zone, representing 41 percent, and roughness and cracking have a greater influence in dry-freeze and dry-no-freeze, representing 70 and 83 percent, respectively.

Table 50. JPCC poor drivers.

Overall Condition	Metrics	Faulting/ Roughness (%)	Roughness/ Cracking (%)	Cracking/ Faulting (%)	Number of Groupings
Poor	G-P-P/ F-P-P	16	62	22	160

There are only two metrics that are used to determine the overall condition for CRCP: roughness and cracking. Both metrics either need to be in good or poor condition for the overall condition to be good or poor, respectively. Table 51 presents the possible combination of metrics that result in fair condition with the exception where both metrics are fair. The G-F, G-P, and F-P groupings represent 93, 2, and 3 percent of the total groupings in fair condition, respectively. The table shows the following:

- The G-F groupings are driven by roughness, which is to be expected, since transverse cracking is not included in the percent cracking calculation for CRCP resulting in lower amounts of percent cracking.
- The numbers of G-P and F-P groupings are too small to make distinctive observations or conclusions.

Table 51. CRCP fair driver.

Overall Condition	Metrics	Roughness (%)	Cracking (%)	Number of Groupings
Fair	G-F	94	6	178
Fair	G-P	25	75	4
Fair	F-P	50	50	6

CHAPTER 6. DEVELOPMENT OF GUIDELINES FOR INFORMING DECISIONMAKING TO AFFECT PAVEMENT PERFORMANCE MEASURES

OVERVIEW

The previous chapter detailed the approach and findings for the threshold, temporal, and performance measure drivers. This chapter summarizes the development of guidelines for informing decisionmaking to affect the pavement performance measures and presents the major components and outcomes of those guidelines. The resulting guidelines are provided under a separate cover in a companion report.(6)

Development of the guidelines built on the findings and processes detailed in this report. More specifically, the guidelines were developed through the following means:

- Use of findings from the development of performance measure drivers.
- Use of findings from assessing the effects of M&R treatments.

The goal of the guidelines is to illustrate to agencies potential strategies to move the overall condition from poor to fair to good. In meeting this goal, the guidelines will enable highway agencies to address critical questions such as the following:

- What are the drivers of the performance measures?
- What are the effects of M&R treatments on condition metrics and overall condition?

The guidelines present recommended procedures for identifying the performance measure drivers and assessing the effectiveness of M&R treatments to improve overall condition and performance measures. The chapters included in the guidelines are summarized below along with a brief description of their contents:

1. Introduction: Provides the background, objectives, and organization of the guidelines.

2. Development of Performance Measure Drivers: Details how to develop the performance measure drivers.

3. Assessing the Effects of M&R Treatments: Presents the effects of M&R treatments on metric and overall conditions.

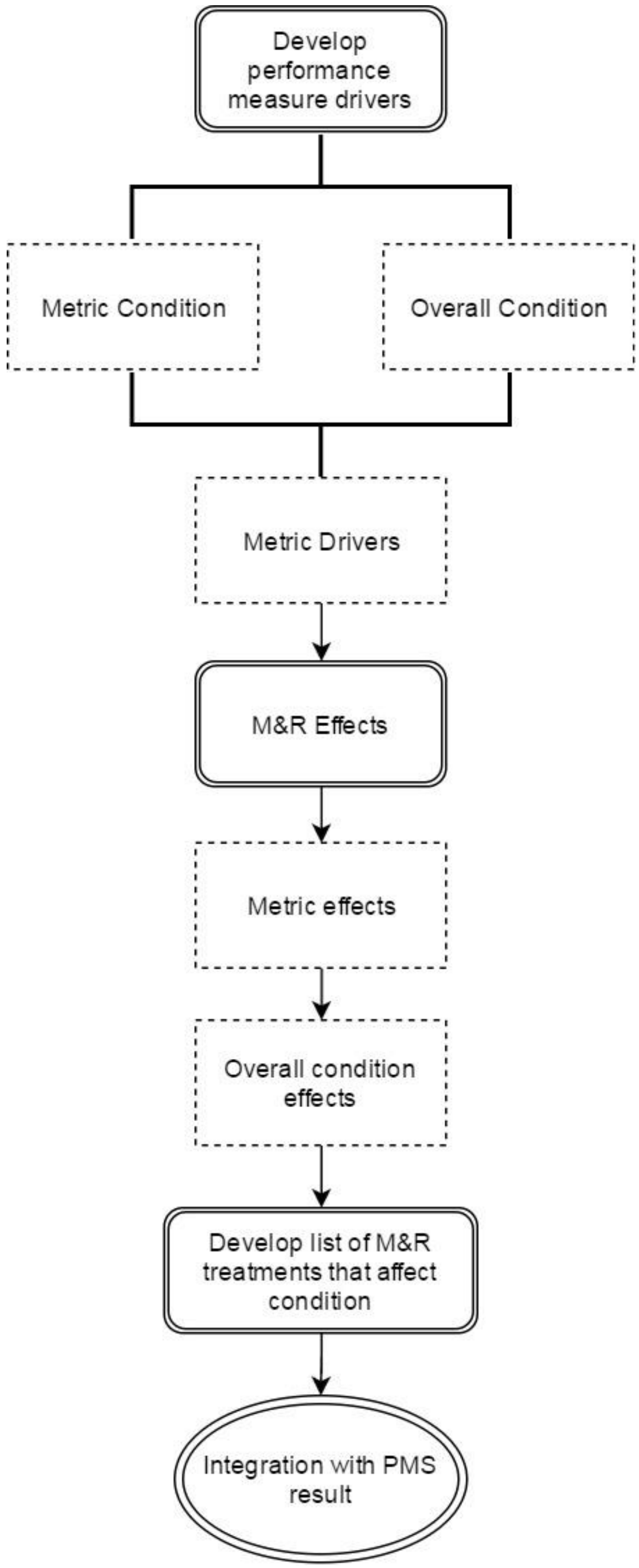
4. Treatments Affecting Performance Measures: Combines the effects of M&R treatments with the performance measure drivers to develop a list of M&R treatments that affect condition.

5. Summary, Challenges, and Recommendations: Summarizes the findings from the previous chapters. In addition, challenges for integrating the findings of the guidelines with PMS results are presented and recommendations made.

The examples, conclusions, and recommendations developed in the guidelines were based on LTPP data. Highway agencies should review and analyze their own data to confirm that the

LTPP-derived information is applicable to their agency and, if not, make the needed adjustments based on the examples provided in the guidelines.

Figure 15 presents a flowchart summarizing the approach detailed in the guidelines. The flowchart begins with the development of performance measure drivers for both the metric condition and the overall condition. The performance measure drivers are then combined with the effects of M&R treatments on the metric and overall condition. These findings are then used to develop a list of potential M&R treatments that affect the condition. The final step in the process is the integration of the results with the PMS.



Source: FHWA.

Figure 15. Flowchart. Guidelines general approach.

DEVELOPMENT OF PERFORMANCE MEASURE DRIVERS

The foundation of all the steps and procedures in the guidelines is the understanding of the metrics for the various pavement types and how the metrics are combined to assign the overall condition. Classifying the metric condition combinations that compose the overall condition is critical throughout the guidelines.

The purpose of developing the performance measure drivers is to identify the metric or metrics that are affecting the overall pavement condition. Knowing the performance measure drivers is necessary in the treatment selection process so that treatments selected address the cause of the pavement condition, improving the individual metrics and, ultimately, the overall pavement condition. To develop the performance measure drivers for each metric condition combination, the guidelines present the following steps:

1. Separate data based on pavement type (e.g., AC, JPCC, and CRCP).

2. Assign condition (G-F-P) for metrics for each pavement section according to table 1.

3. Assign overall condition according to the pavement section metric condition combinations, as explained in chapter 1.

4. Assign each pavement section a metric condition combination (G-F-P, G-G-F, etc.).

5. Identify the metric or metrics that are driving the overall condition for each segment. The driver is defined as the metric or metrics that are most responsible for the overall condition. The driver(s) are identified as follows:

    a. G-G-F: metric in fair condition.
    b. G-G-P: metric in poor condition.
    c. G-F-P: metrics in fair and poor condition.
    d. G-F-F: metrics in fair condition.
    e. F-F-P: metrics in fair condition.
    f. G-P-P/F-P-P: metrics in poor condition.

6. Calculate percentage that each metric is identified in step 5 for the metric grouping to determine the performance measure driver.

Examples are provided for each pavement type using LTPP data to illustrate the steps to develop the performance measure drivers.

ASSESSING THE EFFECTS OF M&R TREATMENTS

To assess the effects of M&R treatments on condition and the performance measures, the time series trends of performance measures against documented M&R treatments were compared. The trends in individual metrics and the overall pavement condition ratings over time were reviewed against recorded M&R treatments to determine whether they demonstrated any type of change in response to those treatments. The guidelines outline how to calculate the change in condition as a result of application of an M&R treatment as well as characterization of the effect of M&R

treatments on the individual pavement metrics and overall condition. The steps required to assess the effects of M&R treatments as presented in the guidelines include the following:

1. Identify pavement sections with a construction event change.

2. Group treatments for pavement sections identified in step 1 into M&R treatment categories based on similarity.

    a. For multiple and different improvements for a single construction event, the improvement should be grouped based on the treatment expected to have greatest influence on pavement surface. For example, crack sealing and shoulder restoration should be classified as crack sealing, since shoulder restoration has no impact on the pavement metrics or overall condition rating.

3. Characterize effect of M&R treatments on individual pavement metrics. The three possible characterization options are the following:

    b. No change in condition—the condition rating before and after treatment remains the same.

    c. Worse condition—the condition rating after the treatment has deteriorated (e.g., before-treatment condition was fair, and after-treatment condition is poor).

    d. Improved condition—the condition rating after the treatment improves (e.g., before-treatment condition was fair, and after-treatment condition is good).

    Examples of this step are provided in the guidelines to provide greater detail, as this is at the heart of assessing the effects of M&R treatments.

4. Characterize effect of M&R treatments on overall pavement condition as no change in condition, worse condition, or improved condition.

Examples for each pavement type are presented in the guidelines.

TREATMENTS AFFECTING PERFORMANCE MEASURES

To develop a list of potential M&R treatments to improve the overall pavement condition (and hence performance measures) from poor to fair, fair to good, and poor to good, the performance measure drivers and the effects of M&R treatments were combined. The steps detailed in the guidelines to accomplish this include the following:

1. Assign data into metric condition combinations (G-F-F, G-G-P, etc.).

2. Determine effect of M&R treatment by comparing overall condition of last survey prior to treatment to overall condition for first survey after treatment as no change, worse, or improved.

3. Calculate percentage that M&R treatment improves condition for each metric condition combination.

4. Evaluate M&R treatments that show improvement, while considering drivers of metric grouping.

5. Develop list of potential M&R treatments.

TEMPORAL ANALYSIS CONSIDERATIONS

Another component that agencies need to consider is the temporal analysis of the metric and overall conditions. The temporal analysis considers the pretreatment condition of the pavement, the treatment type, and the types of change in condition. The guidelines present the following steps to conduct the temporal analysis:

1. Select pavement sections with at least three surveys between construction events.

2. Assign metric conditions and overall condition.

3. Classify the temporal category according to the trend of condition as good to fair; fair to poor; good to poor; fair to good; poor to good; good, no change; fair, no change; or poor, no change.

4. Calculate the time to change condition as the time between the last survey in one condition and the first survey in a different condition or the time that the condition remained constant as the time between the last survey and the first survey after the previous construction event.

POTENTIAL M&R TREATMENTS TO IMPROVE PERFORMANCE MEASURES

Based on the assessments presented in the guidelines, a list of potential M&R treatments that improved the overall condition based on the LTPP data used in the study is presented. The treatments include the following:

- AC pavements.
    - Mill and overlay.
    - Overlay.
    - Surface treatment.
- JPCC pavements.
    - Grinding.
- CRCPs.
    - PCC overlay.

Agencies should follow the procedures provided in the guidelines to develop, using their data, a similar list of treatments that improve the overall condition.

The guidelines conclude with a summary, challenges, and recommendations for State DOTs to consider when implementing the performance measures within the agency. The challenges presented in the guidelines include the following:

- **Different data sources**. The performance measures to assess pavement condition are to be based on HPMS data. Although States DOTs are required to submit HPMS data annually, the HPMS data submittal does not always match the data that an agency maintains in their PMS.

- **Change in optimization goals**. Agencies have various optimization goals for their PMS and treatment selection. Agencies will need to decide how the performance measures will affect their decisionmaking process. As a minimum, it is recommended that agencies consider how PMS outcomes (i.e., recommended M&R and project prioritization) impact the performance measures and determine whether the performance measures should be incorporated into the decisionmaking process.

- **Updating models within the PMS to consider the performance measures**. A key component of PMS is the predictive models for the effect of various types of treatments and deterioration models. For agencies to incorporate the performance measures within the decisionmaking process, models used within the PMS would need to be updated or developed based on the performance measures and these factors used to predict the effect of treatments on the performance measures.

Agencies are required to meet the performance measures or face loss of flexibility for spending NHPP funds until the minimum required condition levels are exceeded. Therefore, it is critical that agencies understand what metrics drive the performance measures and how performance measures are affected by M&R treatments and, based on that information, determine how the performance measures will be incorporated into their decisionmaking process. As a minimum, it is recommended that agencies add the performance measures to the output of the PMS and treatment selection optimization to monitor the values of the performance measures. It is also recommended that agencies perform similar analyses as those described in the guidelines and develop a list of potential M&R treatments that affect the performance measures. Furthermore, it is recommended that agencies incorporate these suggestions based on a long-term view of the overall health of their networks.

CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter provides a summary of the findings as a result of the review and validation of pavement performance measures presented in the previous chapters.

A literature review identified a set of criteria to be used in evaluating performance measures, and the following conclusions were drawn:

- Comprehensive—the performance measures are comprehensive with respect to the state of the practice.
- Balanced—the performance measures are balanced, as they comprise four individual metrics for IRI, cracking, rutting, and faulting.
- Able to show trends—the analyses showed that the performance measures are largely static though they were impacted by M&R events.

The following bullets summarize the major findings of the review and validation effort:

- Significant roughness, cracking, rutting, or faulting was not observed on LTPP test sections. This may be, in part, the result of the nomination and selection process being biased toward test sections in good condition for the LTPP program.
- Changes in IRI, cracking, rutting, and faulting within and between construction events appear rational and logical.
- IRI, cracking, rutting, and faulting provide measures of condition that meet requirements identifying repair needs (i.e., IRI is the most important user metric, cracking and faulting show the need for M&R, and rutting shows M&R and safety needs).
- Measurement accuracy is important for rutting and faulting.
- Faulting measurements need to be more accurate than 0.05 inch, but this may not be possible at high speeds.
- Individual pavement metrics (IRI, cracking, rutting, and faulting) generally increase (worsen) over time within construction events.
- Overall pavement condition ratings follow the expected trend from good to fair to poor 90 percent or more of the time except for JPCC where it is 83 percent.
- Individual pavement metrics (IRI, cracking, rutting, and faulting) are generally affected by M&R activities.
- Overall pavement condition is largely unaffected by M&R activities. Overall pavement condition is static and remains constant more than 60 percent of the time and for at least 3.8 yr.

- Overall pavement condition for AC pavements is driven by the cracking and rutting condition. Cracking most often contributes to the overall condition being fair when the metric is in poor condition. Rutting contributes more often to the overall condition of fair when the metric is in fair condition than other metrics.

- Overall pavement condition for JPCC pavements indicates that IRI and cracking drive the overall poor condition more so than faulting. It also shows that IRI may have a larger impact on overall pavement condition being fair than the other metrics, since when IRI is in fair condition, the overall condition is fair 70 percent of the time.

- Overall pavement condition for CRCPs is driven by IRI, as when IRI is in fair condition, the overall pavement condition is fair 93 percent of the time.

- Performance measures for AC pavements benefit from M&R activities as the percentage good increases and the percentage poor reduces.

- Performance measures for JPCC pavements did not show a benefit from M&R activities as the percentage good reduced and the percentage poor increased.

- Performance measures for CRCPs generally benefit from M&R activities as the percentage good increases but the percentage poor also increases. This is likely a result of there being few pavements in poor condition as well as the fact that patching, which is considered an M&R activity, does in fact increase the percent of cracking for CRCPs and therefore could have a negative impact on condition and hence cause the percent poor to increase.

- For the AC and CRCPs, the alternate thresholds were observed to have an impact at the metric level, but less of an effect on the overall pavement condition and performance measures. A much larger effect was observed at the overall condition and subsequent performance measures on JPCC pavements with a 7-percent increase in good condition. This increase is due to the change in the threshold for the faulting condition metric.

- Overall pavement condition ratings are stable over time, as shown by the temporal analysis. A minimum average time from the first survey after construction to the first survey showing a change in condition of 4 yr was determined for AC pavements. This estimate is conservative, as it does not include the time from construction to the first survey. For the LTPP sections used in this analysis, the average time from construction to the first survey is 1.5 yr. For JPCC and CRCP, the minimum average time to change is significantly higher, with CRCP having the largest time.

- Some differences may be observed in the time for the overall condition to change for different climate zones with the largest differences observed on JPCC and CRCP sections.

- Cracking is the metric most likely to be poor for AC pavements. Rutting may be identified as the secondary driver for AC pavements with this metric being identified from analyses of the G-G-F overall condition and in those instances where two of the metrics are in fair or poor condition. The strength of these conclusions varies slightly when the data are viewed by climate zone or route type, although these two metrics are dominant for all climate zones and route types.

- Faulting and roughness together are largely the drivers of fair condition for JPCC pavements when there are two metrics that are fair. Roughness and cracking are the primary drivers for the poor condition of JPCC pavements. As with the AC pavements, the strength of these conclusions varies slightly when the data are viewed by climate zone or route type, although these two metrics are dominant for all climate zones and route types.

- Roughness is the driver for the CRCP fair condition. This is a result of low average values for percent cracking, since percent cracking only considers longitudinal cracking in the wheel path and punchouts and not transverse cracking.

- All metrics were shown to be drivers of overall condition at some point. This supports the conclusion that the metrics selected as part of the Final Rule appear correct.

- Rutting is more likely to be the driver in wet-no-freeze zones than other climate zones, suggesting that in wetter and warmer climates, rutting is a bigger issue.

- Emphasis should be placed on borderline groupings of metrics when trying to improve the condition from fair to good or from poor to fair or when trying to prevent the condition from falling from fair to poor.

Based on the above findings, guidelines for informing decisionmaking to affect the pavement performance measures were developed. The resulting guidelines are provided in a companion report.(6)

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