Development of Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Objectives

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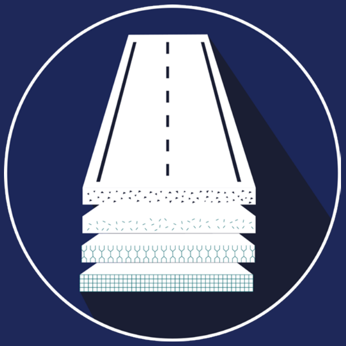

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Federal Highway Administration

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FOREWORD

In 2015, the Federal Highway Administration (FHWA) initiated a project titled Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements (FHWA n.d.a). This report documents research undertaken as part of this project's second phase to test, refine, and validate several next-generation pavement performance measures and a proposed transportation asset management methodology (TAMM) implemented in pilots at three State departments of transportation (DOTs) and FHWA. The report details each performance measure, the proposed TAMM, and the approach used to select the three pilot State DOTs. The report also documents the validation activities performed at each agency and FHWA and presents the results of each validation study. Additionally, it presents strategies for implementing the new performance measures and TAMM—including suggestions for making necessary changes to existing datasets and systems—and outlines the main conclusions about their suitability and effectiveness in lifecycle planning.

This report should be informative to pavement management and bridge management engineers, asset managers, and State DOT executives responsible for highway investment and programming decisions. Additionally, highway data collection service providers and asset management vendors may find this information useful.

Jean A. Nehme, P.E., Ph.D.
Director, Office of Infrastructure
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<tr><td colspan="4">16. Abstract
The Moving Ahead for Progress in the 21st Century Act (MAP-21), the Fixing America’s Surface Transportation Act, and other current legislation promote the use of performance-based decisions to manage the Nation’s highway system (U.S. Congress 2012, 2015). MAP-21 identified seven national goal areas and established requirements for national performance measures for pavements and bridges and the development and implementation of risk-based transportation asset management plans by State departments of transportation (DOTs) (U.S. Congress 2012). Fulfilling these requirements has helped highway agencies advance data-driven investment decisions that maximize return on public investment in the highway system and maintain a state of good repair for highway infrastructure assets. Although the condition-based performance measures meet the immediate needs under the legislation, FHWA initiated research to explore “next-generation” pavement performance measures (NGPPMs) that are more proactive in driving investment decisions that lead to enhanced long-term performance. FHWA also investigated the feasibility of a methodology to help transportation agencies manage their highway infrastructure as a system rather than a network of individual asset classes. The research was initiated in 2015 as a two-phased effort titled <u>Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements</u> (FHWA n.d.a). Phase I identified eight promising NGPPMs (not currently required under any Federal legislation) highway agencies could use as leading indicators for long-term investment strategizing and decisionmaking, along with two promising transportation asset management methodologies (TAMMs). In phase II, after further development and analysis, seven of the promising NGPPMs and one of the proposed TAMMs were piloted at the State level to validate their use. The study also sought to validate the performance measures at the Federal level. This report details phase II.</td></tr>
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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ACLM	annualized cost per lane-mile
ACR	asset consumption ratio
ASI	asset sustainability index
ASR	asset sustainability ratio
AUCR	annualized unit cost ratio
BCA	benefit-cost analysis
BCR	benefit-cost ratio
BMS	bridge management system
BRR	backlog reduction ratio
CAR	cost accrual ratio
CFR	Code of Federal Regulations
CRC	continuously reinforced concrete
CRV	current replacement value
CS	condition score
DOT	department of transportation
DRV	depreciated replacement value
EUAC	equivalent uniform annual cost
FAST	Fixing America's Surface Transportation (Act)
FHWA	Federal Highway Administration
FN	friction number
FWD	falling weight deflectometer
HDM-4	Highway Development and Management Model Four
HERS	Highway Economic Requirements System
HPMS	Highway Performance Monitoring System
ID	identification
IRI	international roughness index
ITD	Idaho Transportation Department
JPC	jointed plain concrete
LCCA	lifecycle cost analysis
LCC	lifecycle cost
LCP	lifecycle planning
LOS	level of service
MAP-21	Moving Ahead for Progress in the 21st Century Act
MBCB	maximum benefit at current budget
MBU	maximum benefit at unlimited budget
NBIAS	National Bridge Investment Analysis System
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NGPPM	next-generation pavement performance measure
NDI	nonstructural distress index
NHS	National Highway System
NPV	net present value
OCI	overall condition index

PMS	pavement management system
PSR	present serviceability rating
PV	present value
RSI	remaining service interval
RSL	remaining service life
RV	remaining value
SCI	surface condition index
SDDOT	South Dakota Department of Transportation
SDI	structural distress index
SHS	State highway system
SLR	stewardship liability ratio (formerly known as BRR)
SOC	simple option cost
SOGR	state of good repair
TA-MAPO	tradeoff analysis for multiasset performance objectives
TAM	transportation asset management
TAMM	transportation asset management methodology
TAMP	transportation asset management plan
TSDD	traffic speed deflection device
TxDOT	Texas Department of Transportation
UPDAPS	Development of Models and a Framework for a Unified Pavement Distress Analysis and Prediction System

EXECUTIVE SUMMARY

INTRODUCTION

The Moving Ahead for Progress in the 21st Century Act (MAP-21), the Fixing America's Surface Transportation (FAST) Act, and other current legislation promote the use of performance-based decisions to manage the Nation's highway system (U.S. Congress 2012, 2015). MAP-21 identified seven national goal areas and established requirements for national performance measures for pavements and bridges and the development and implementation of risk-based transportation asset management plans by State departments of transportation (DOTs) (U.S. Congress 2012). Fulfilling these requirements has strengthened highway agencies' abilities to make data-driven investment decisions that maximize return on public investment in the highway system and maintain a state of good repair (SOGR) for highway infrastructure assets (FHWA 2019).

Although the MAP-21 legislation's condition-based performance measures meet immediate needs, next-generation pavement performance measures (NGPPMs) that are increasingly proactive in driving investment decisions that lead to enhanced long-term performance are still needed. Additionally, a procedure or tool to help agencies manage their infrastructure as a system rather than a network of individual asset classes is needed. This study was established to address these needs. Its objectives included the following:

- Developing, testing, and validating (through pilot implementation) promising NGPPMs and transportation asset management methodologies (TAMMs).

- Developing guidance on modifying existing asset management systems to better support the use of a broad range of performance measures and dynamically conduct cross-asset tradeoff analysis.

This study successfully validated several NGPPMs, proposed TAMMs at three State DOTs (Idaho, South Dakota, and Texas), and produced valuable insights for other agencies interested in implementing and using these techniques and methodologies.

NEXT-GENERATION PAVEMENT PERFORMANCE MEASURES

Agencies need performance indicators in multiple areas to develop understanding of pavement performance and investment needs and make sound long-term investment decisions. Performance measures that enable the implementation of a comprehensive asset management program can be grouped into three broad categories, as follows:

1. Condition measures that are specific to an asset class and agency (e.g., pavement roughness, rutting, and cracking; an agency's rating scale of pavements in Good/Fair/Poor conditions (Office of the Federal Register 2017).

2. Lifecycle measures that provide information on the lifecycle cost (LCC) of maintaining a pavement network.

3. Financial measures that describe the financial sustainability of an agency's pavement management program.

Current and projected conditions are the most common indicators of pavement performance. Pavement conditions deteriorate over time and with use. Performing preservation, rehabilitation, or reconstruction activities maintains or improves the asset condition according to the action performed. Condition is generally considered a measure that is physically observable through a standard rating protocol (e.g., cracking and rutting for pavements). Condition measures are currently used in pavement management systems (PMSs) and are predicted into future years using established deterioration models (Pierce, McGovern, and Zimmerman 2013). This modeling enables the agency to ascertain the cost-effectiveness of applying treatments at different points in time. Applying this process to an entire network provides agencies with the information needed to evaluate different investment strategies. Most agencies already have a procedure to rate asset conditions and use these measures in their asset management process to make treatment and investment decisions. Hence, condition-based performance measures were not the focus of this study.

Lifecycle performance measures characterize and monetize the long-term investment strategies (i.e., construction, maintenance, and rehabilitation treatments) associated with providing a desired level of service (LOS) for a highway asset. These measures proactively encourage activities that reduce the long-term cost of managing the system. Thus, their focus is on the evaluation of strategy cost-effectiveness and achieving the highest overall system performance at the lowest practicable LCC. The project team evaluated three lifecycle measures, as follows:

- The remaining service interval (RSI) approach uses a structured sequence of maintenance, preservation, rehabilitation, and replacement actions through LCC considerations to provide acceptable service over asset life at minimum practicable cost. It focuses on the "when" and "where" aspects of treatment application to iteratively determine the most cost-effective sequence of treatments to maintain pavements over an extended planning horizon (Elkins et al. 2013).

- The annualized unit cost ratio (AUCR) measures the ratio of the programmed equivalent uniform annual cost (EUAC) per lane-mile of all expenditures over the pavement's lifecycle to the optimized EUAC per lane-mile. This measure helps visualize the magnitude of the deviation from the optimized lifecycle strategy using a simple, intuitive metric.[1]

- The cost accrual ratio (CAR) compares the planned investments in an agency's asset lifecycle strategy to the optimized lifecycle plan for the same asset, which will theoretically result in the lowest LCCs. The CAR can also help evaluate the financial sustainability of different lifecycle strategies evaluated by the agency.[2]

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[1] Sadasivam, S., and J. Mallela. 2017. *Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements, Vol. I: Pavement Performance Measures*. Unpublished internal report for phase I of project. Washington, DC: Federal Highway Administration.

[2] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.

Financial performance measures indicate if an adequate level of investment is being made to offset the rate of asset value depreciation or satisfy treatment needs to meet condition targets now and in the future. The project team evaluated four different financial measures, each of them providing unique information on the financial sustainability of an agency's investment approach, as follows:

- The asset sustainability index (ASI) is the ratio of the budget allocated to the amount needed to address all current management system treatment selections. The ASI helps decisionmakers determine the adequacy of investments to address needs identified by the PMS (Proctor, Varma, and Varnedoe 2012).
- The asset sustainability ratio (ASR) is the ratio of asset maintenance, preservation, and replacement expenditure to asset depreciation for a given time. The ASR helps decisionmakers determine whether sufficient investments have been made to offset asset value depreciation (Ram et al. 2023).
- The asset consumption ratio (ACR) is the ratio of depreciated asset replacement cost to current replacement value (CRV). The ACR highlights the average proportion of as-new/as-built condition that is left (Ram et al. 2023).
- The stewardship liability ratio (SLR) is the ratio of the unfunded treatment needs/backlog to the CRV. The SLR can be used to measure the rate of change of backlog over time compared to the replacement value of the pavement work. The SLR was previously known as the backlog reduction ratio (Ram et al. 2023).[3]

Each performance measure evaluated in this study can help transportation agencies answer questions that are important to drive cost-effective investments, monitor long-term pavement performance, and measure the overall effectiveness of the pavement management program.

PROPOSED TRANSPORTATION ASSET MANAGEMENT METHODOLOGY

A proposed TAMM was developed to support tradeoff analysis among multiple objectives and multiple asset classes that are traditionally managed separately, including, at a minimum, pavements and bridges. The challenge in developing this methodology was to fairly reflect the diverse ways that different asset classes can affect road users and transportation system objectives. The research team wanted this methodology to be attainable in an objective way, using data from asset management systems, as currently conceived if current Federal rules (23 Code of Federal Regulations (CFR) 515) are fully implemented (CFR 2021b). The tradeoff analysis should address common planning use cases in a way that is familiar and implementable for State DOTs and other transportation infrastructure owners.

Transportation asset management systems often integrate a tradeoff analysis with a priority setting, as both functions require compatible expressions of objectives and constraints. Thus, the methodology was conceived as a prioritization approach, whose value is sensitive to the most common effects of each asset class and whose calculation can be made sensitive to common performance goals, including condition, cost, safety, and mobility. Existing analysis tools for

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[3] Zimmerman, K. A., B. W. Allen, P. V. Ram, G. M. Duncan, O. Smadi, K. L. Smith, K. R. Manda, and B. A. Bektas. 2016. *Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements*. Unpublished internal report for phase I of project. Washington, DC: Federal Highway Administration.

asset management provide LCC models and user cost models with the desired sensitivity, which can be calculated using commonly available management system data.

Therefore, the methodology was designed to use social cost to evaluate tradeoffs—specifically, the savings in social cost if an investment is selected in the present rather than delayed. Presumably, the agency keeping its network in service is a long-term social concern, so the tradeoff analysis can be formulated as a problem of minimizing social cost. This problem includes the consideration of long-term agency and user costs, either combined or separate, depending on agency preferences. The situation is constrained by funding availability and the desire to keep the network operational at the desired LOS. Existing models and research provide practical ways of computing the cost components. Ultimately, the proposed TAMM is used in the same way as any benefit-cost ratio (BCR) and is compatible with common algorithms for priority setting and tradeoff analysis under fiscal constraints (Coley 2012).

Since some of the pavement performance measures are based on LCC, the research team assumed that eventually (if not currently) PMSs will be able to perform an LCC calculation. During the pilot studies, the research team determined that social costs are not commonly generated in a PMS analysis and that challenges arise with comparing pavement condition measures with condition measures for other asset classes. As a result, the pilot studies needed to provide a temporary means, implemented in spreadsheets, to bridge the gap between the existing PMS and desired capabilities.

The three pilot agencies were in various stages of implementing the AASHTOWare™ Bridge Management software (BrM) (AASHTO 2023). As such, all were managing similar sets of bridge inventory, condition, and performance data and had (or were developing) similar models for bridge deterioration and cost. The widespread standardization of bridge management tools was helpful in designing an analytical process compatible with common data and management practices. However, in its current form, the BrM is designed to offer detailed analysis for project-level use cases and does not have the mature tools for rapid analysis supporting network-level applications (AASHTO 2023). Thus, StruPlan, an open-source spreadsheet tool, was used to process bridge management system data and models in a manner more responsive to the needs of a network-level tradeoff analysis because it could generate a full set of investment candidates with LCCs (Thompson 2021).

Pavement and bridge social cost metrics were combined in the Tradeoff Analysis for Multiasset Performance Objectives (TA-MAPO) spreadsheet tool (FHWA 2024b). This tool uses a simple benefit-cost analysis in a form commonly found in management systems and capital budgeting analytical tools. The tool sets priorities among diverse investment candidates using a benefit-cost prioritization measure based on long-term social cost. The tool can evaluate multiple fiscal scenarios and vary funding allocations among performance goals, asset classes, and subnetworks to satisfy policy requirements or achieve a set of performance targets while minimizing long-term social cost. The tool was conceived as a working prototype, implementable as-is but more likely to be incorporated into tools agencies use or develop to support asset management planning workflow.

KEY FINDINGS OF STATE VALIDATION STUDIES

Idaho Validation

Next-Generation Pavement Performance Measures

The RSI analysis could not be implemented using the current PMS analysis configuration of the Idaho Transportation Department (ITD), since the data elements required for the RSI analysis were not included in the standard analysis outputs (Kercher Engineering 2015). Notably, ITD's PMS could be customized and configured with the capability to run an RSI analysis; however, the agency had not fully implemented the analysis modules required for this analysis at the time of the validation effort. Additionally, the performance models programmed within ITD's PMS were not responsive to pretreatment pavement condition. Hence, the team developed an ad hoc approach to simulate the RSI analysis using ITD's decision trees and performance models. However, this approach required exceedingly long computation times for a 40-year analysis period. As a result, the approach was deemed impractical for implementation purposes and was not pursued further.

The ASR and SLR measures provided valuable insights, and ITD was interested in implementing these measures in the future as a part of their asset management processes. The projected condition trends based on ITD's existing pavement condition measure (determined from pavement distresses) suggested that the pavement network will remain in Fair or better condition over the long term (40-year analysis period) (Poorbaugh 2017; ITD 2022). However, the ASR and SLR measures painted an extremely different picture. After 15 years, the ITD budget level used in the analysis was not adequate to offset expected asset value depreciation. Moreover, the long-term SLR trends suggested that a change in pavement treatment strategies would be needed within the next 15 years to keep the backlog growth rate in check.

Transportation Asset Management Methodology

Idaho's pilot test of the tradeoff methodology and the TA-MAPO tool successfully demonstrated the proposed TAMM and the desired scenarios. Unweighted BCRs based on social cost produced reasonable resource allocations and performance outcomes. The analysis tended to make overall performance more uniform over the network. Adjustments to the weights used in the prioritization measure had the desired effects of giving added emphasis to selected performance concerns.

South Dakota Validation

Next-Generation Pavement Performance Measures

By using treatment-specific decision trees and performance models that take into consideration pretreatment pavement conditions, the South Dakota Department of Transportation (SDDOT) PMS was able to generate all feasible pavement lifecycle treatment strategies for each segment included in the network. The use of network-level data was originally anticipated for the RSI validation. However, because the PMS required substantial computational times for a 30-year multistrategy analysis run, the team opted to use pavement data for a small roadway corridor for the NGPPM validation.

The network-level LCC computed using SDDOT's PMS was comparable to the results from the lowest LCC strategy generated using the RSI analysis. This similarity indicates that the current configuration of SDDOT's PMS generates treatment strategies that are close to the lowest LCC solution. The AUCR and CAR measures were found to be useful in comparing various treatment strategies that provided similar performance outcomes over the analysis period.

The ASR was found to be the most useful financial measure, providing information on the effectiveness of each treatment strategy in offsetting asset value depreciation. The ASI and ACR measures did not provide insights that were different from what could already be gleaned through SDDOT's existing pavement condition measure. The SLR could not be validated since SDDOT's PMS did not report the backlog of unfunded treatment needs.

Transportation Asset Management Methodology

Similar to ITD's situation, SDDOT was not yet able to calculate social impacts within its management systems, although the agency did have the essential data these calculations required. Therefore, external spreadsheets were used to perform the calculations. The bridge computations obtained using StruPlan were similar to the computations used in Idaho and worked well (Thompson 2021). However, the SDDOT pavement computations were more difficult, largely due to software limitations and limited access to data in the PMS. Ultimately, the pavement dataset did not have enough pavement investment candidates to enable a tradeoff analysis against bridges. This candidate shortage was not caused by problems with data or pavement investments; rather, the shortage was caused by the PMS's inability to calculate LCCs that corresponded to varying treatment strategies.

Although the pilot study did not produce implementable results, it did help develop a better, more precise specification of the benefit-cost prioritization methodology (FHWA 2024b). This outcome supported the study's goal of documenting improvements to existing management systems that would support next-generation cross-asset tradeoff analysis.

Texas Validation

Next-Generation Pavement Performance Measures

Like ITD, Texas Department of Transportation (TxDOT) had a standard PMS analysis module that could not be used to conduct the RSI analysis. Thus, the results from TxDOT's PMS analysis were only used to validate the financial performance measures. The research team then performed analyses independently for two TxDOT districts: Houston and Brownwood.

The ASR and SLR measures appeared to be more useful in providing information that could be used in the decisionmaking process. For both the Houston and Brownwood districts, the ASR exhibited a sharply declining trend over the first 5 years before the values generally leveled out. This trend suggested that additional investments in heavier treatments are needed in the initial years to offset asset value depreciation effectively.

A decrease in funding level had a bigger impact on the projected SLR for Brownwood District than it did for Houston District. One potential reason for this difference was that Houston District was composed of mostly concrete pavements with longer estimated lifecycles; meanwhile, Brownwood District only included asphalt-surfaced pavements with relatively shorter lifecycles. For Brownwood District, the impact of reducing the funding level became apparent at year 6 of the analysis, which could suggest the need for additional funding or treatment strategy changes within the first 6 years of the analysis period.

Transportation Asset Management Methodology

As with the Idaho and South Dakota validation efforts, detailed pavement and bridge data were requested and provided by TxDOT, processed into investment candidates with LCC, and then entered into the TA-MAPO tool to analyze tradeoffs among costs and conditions across asset classes and subnetworks. As was the case with SDDOT, the pavement dataset did not have enough investment candidates to support a cross-asset tradeoff analysis. Since TxDOT had not completed its development of bridge deterioration and cost models, the bridge results also were not sufficiently mature to be implementable. Despite these issues, the TA-MAPO did have enough information to demonstrate the desired tradeoff behavior. For example, the weights assigned during the sensitivity analysis for condition, safety, and mobility affected forecast outcomes as anticipated. Changes in the total funding provided to the model had the expected effects on performance outcomes (FHWA 2024b).

KEY FINDINGS OF THE FEDERAL VALIDATION STUDY

In addition to validating NGPPMs at the State level, this study sought to validate the measures at the Federal level using data from the Federal Highway Association (FHWA) Highway Performance Monitoring System (HPMS) database and the modeling and analytics of the Highway Economic Requirements System (HERS) software (FHWA 2016, 2005). The validation efforts were focused on three lifecycle measures (RSI, AUCR, and CAR) and four financial measures (ASI, ASR, ACR, and SLR) (Elkins et al. 2013; Proctor, Varma, and Varnedoe 2012; Ram et al. 2023).[4] To apply the NGPPMs at the Federal level, an assessment of the data needs was required. One of the key challenges in conducting the Federal validation study was the availability of pavement management data at the Federal level. To complete the data assessment, the research team analyzed the three lifecycle performance measures and the four financial performance measures to compare the data required with the data available from the HPMS database and the HERS software analysis results (FHWA 2016, 2005). The State of Idaho was selected for this analysis, since the research team was making progress calculating the State-level NGPPMs.

Unfortunately, the data available at the Federal level were too limited to support the calculation of the NGPPMs; thus, the Federal validation assessment proved infeasible. Additionally, the ITD HPMS data and the ITD pavement management results data were provided using geographic information systems to facilitate the linking of road segments (FHWA 2016). However, that process proved infeasible due to the lack of a common referencing system.

The validation study results did indicate that two of the seven NGPPMs, the RSI and the ASI, hold the most promise for implementation and use at the Federal level. The research team also determined that enhancements to processes and tools (for HERS) and additional data requirements (for HPMS) would be needed for some of the NGPPMs to be calculated at the national level (FHWA 2016, 2005).

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[4] Sadasivam and Mallela. *Identification of Effective. . .Vol. Ⅰ: Pavement Performance Measures.*

ANTICIPATED USE OF THE FINDINGS

Next-Generation Pavement Performance Measures

Even without a full implementation, State DOTs can start using the NGPPMs evaluated under this study in conjunction with traditional condition-based measures to better understand their usefulness in the pavement management decisionmaking process. Some short- and long-term strategies for practical use are as follows:

- Short-term strategies (less than 5 years):
    - Calculate NGPPMs and compare the results to existing agency-based condition measures to see if the measures can help provide a more informed account.
    - Use measures to communicate differences between various treatment strategies and funding levels evaluated by the agency for a nontechnical audience.
    - Pilot use of NGPPMs within a district, region, or county to validate pavement management treatment decisions at both network and project levels.
    - Conduct training for PMS practitioners on how the measures can be implemented immediately through the development of simple tools that can be used in conjunction with PMS data.
- Long-term strategies (5 to 10 years):
    - Work with PMS vendors to make necessary adjustments to enable calculating the measures within the PMS without other supplemental tools.
    - Use financial measures to validate pavement management decision trees. Is the PMS recommending the right type of treatment at the right time to help offset long-term asset value depreciation?

A key enhancement needed in the next generation of PMSs is the ability to evaluate all feasible treatment strategies without relying exclusively on decision trees. Many of the PMS tools available today are able to generate multiple treatment strategies for each pavement segment in the network. However, the strategies developed still rely heavily on the rules established using the decision trees. Decision trees rely on predetermined thresholds for distress, pavement condition metrics, and/or other performance indicators (cracking, rutting, overall condition index (OCI), international roughness index (IRI), etc.) (CFR 2017b). The use of these somewhat arbitrary treatment trigger thresholds may potentially result in the true optimal solution being missed. Artificial constraints imposed by decision trees may be eliminated if the PMS considers treatment options based on the ability to maintain pavement above selected performance criteria instead.

Implementing the NGPPMs will provide agencies with an enhanced ability to assess and compare pavement management strategies and make decisions that are not only cost effective in the short-term but also provide the best return on investment over the lifecycle. Following is a summary of the main benefits that can be realized through the implementation of the NGPPMs:

- Identifying pavement treatment strategies that result in the lowest practicable LCC: The lifecycle approaches and measures evaluated and validated in this study (RSI, CAR, and AUCR) will help agencies assess the effectiveness of the pavement management strategies selected by comparing the planned expenditures and performance outcomes to the optimized strategy. This comparison will help agencies make necessary adjustments to strategies being implemented to minimize deviation from the optimized strategy.

- Narrating an account that may not be obvious from condition-based performance measures alone: Using NGPPMs may help agencies learn information beyond what condition-based indicators would have shown them. Financial measures such as ASI, ASR, and SLR will help agencies evaluate the effectiveness of their investment approaches in meeting and sustaining the desired SOGR (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). Additionally, these measures will indicate the impact of the treatment strategies in maintaining asset value and keeping the backlog growth rate in check. They also provide a leading measure that can be used to drive investment decisions. The time-series trends exhibited by these measures can help identify if and when a significant shift in the pavement management approach may be needed. Using financial performance measures in conjunction with lifecycle measures can help agencies identify lost opportunities and plan for adjustments that will be needed to prepare for future funding needs. As decisionmakers become more familiar with LCC concepts and the NGPPMs, this familiarity can also help inform cross-asset decisions.

- Communicating performance outcomes using measures that resonate with decisionmakers: The use of traditional performance measures, such as IRI, pavement distress, and OCI, may not necessarily resonate with decisionmakers within agencies. The financial measures evaluated in this study communicate pavement network performance using simple, intuitive indicators that do not require specialized pavement management knowledge.

Transportation Asset Management Methodology

The proposed TA-MAPO uses sorting and summarization methods, based on benefit-cost optimization, which are often found in capital programming spreadsheets and are readily supported by common software. The TA-MAPO tool was developed as a proof-of-concept for the analysis and may potentially be implemented by transportation agencies (FHWA 2024b). However, agencies are more likely to incorporate the methods used in the TA-MAPO into their already existing information systems to support various renewal planning processes. For example, all State DOTs have sets of reports (usually in internal agency formats evolved over many years of use) that are essential for their annual or biennial budgeting and programming activities. It may not be necessary to re-create these reports in a new system if incorporating the proposed tradeoff analysis within the existing systems is easier. Any implementing agency may want to consider this approach, perhaps using the TA-MAPO tool as a working prototype.

If an agency's current process for budget allocation is simply the continuation of historical norms, the idea of using a tradeoff analysis may be new. Using a tradeoff analysis requires a willingness among stakeholders to consider changes in historical allocations, which may also imply changes in staffing and other resources and affect future construction plans. Part of the value of using an economic performance measure for evaluation of tradeoffs is the ability to estimate the economic benefit of a change in historical norms. The benefit can then be weighed against the costs. A tool similar to the TA-MAPO tool can be used to explore multiple scenarios, including the possible need to implement funding allocation changes in successive phases to provide the necessary time for the agency and industry to adapt.

The benefits of the proposed TAMM lie in the ability to manage an infrastructure network as a whole, maintaining an appropriate balance in resource allocations and performance among all the components of the network. Thus, the desired LOS is provided at the lowest long-term cost, considering the differential levels of deterioration rates, cost, and risk that exist within the network. Elements of these benefits include the following:

- Existing management systems can continue their own lifecycles independently, taking advantage of the long-standing frameworks, expertise, training, tools, and research that exist within each disciplinary area.
- Agencies can evaluate differences in performance among network components objectively and equalize them as appropriate to best serve public needs.
- Agencies can justify remaining performance differences with objective analysis, which helps avoid unintended misallocation, especially among socioeconomic classes of users and between geographic areas.
- Agencies can allocate increments of transportation funding to network components that can most effectively use the funds to improve network performance.
- Agencies can minimize long-term costs to keep the network in service.
- Agencies can estimate benefits of infrastructure renewal more consistently and completely with the advent of the TAMM and can more easily communicate these benefits to stakeholders.
- Agencies can allocate risk of extreme events, climate change, and advanced deterioration and balance these risks consistently across all network components.

All these benefits are intrinsic to the promise of asset management, a promise that the proposed TAMM will help to realize.

CHAPTER 1. INTRODUCTION

BACKGROUND AND PROBLEM STATEMENT

The Moving Ahead for Progress in the 21st Century Act (MAP-21), Fixing America's Surface Transportation (FAST) Act, the National Highway Performance Program, and the National Goals and Performance Management Measures promote the use of performance-based decisions to manage the Nation's highway system (U.S. Congress 2012, 2015; Code of Federal Regulations (CFR) 2019, 2021a). Under MAP-21, seven national goal areas were identified, and the Secretary of Transportation was responsible for establishing national performance measures and standards through a rulemaking process. The resulting performance measures for pavements address pavement conditions on the interstate system and on the non-interstate National Highway System (NHS). In addition to establishing pavement performance measures, MAP-21 includes a requirement for State departments of transportation (DOTs) to develop and implement a risk-based transportation asset management plan (TAMP) that does the following (U.S. Congress 2012):

> Shall include strategies leading to a program of projects that would make progress toward achievement of the State targets for asset condition and performance of the NHS in accordance with section 23 USC 150(d) and supporting the progress toward the achievement of the national goals identified in section 23 USC 150(b).

These requirements provide an opportunity for transportation agencies to use performance data to strengthen the use of data-driven investment decisions that maximize return on public investment in the highway system and maintain highway infrastructure assets in a state of good repair (SOGR). Developing and implementing a TAMP encourage the use of business processes that focus on managing assets for the long term and at the lowest practical cost.

Although the MAP-21 pavement condition-related performance measures meet immediate needs, a need exists to identify and integrate next-generation pavement performance measures (NGPPMs) that proactively drive investment decisions leading to enhanced long-term performance. In addition to identifying and developing NGGPMs, agencies desire the ability to use the measures and corresponding data effectively to manage the highway infrastructure as a system rather than a network of individual asset classes.

To address these deficiencies and needs, the Federal Highway Administration (FHWA) initiated a two-phase research project in 2015 titled Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements (FHWA n.d.a). The project was implemented in two phases. Phase I, which was completed in 2016, included separate awards to four different contractors, who were asked to explore different approaches to developing the NGPPMs and a cross-asset analysis methodology. Phase I resulted in the identification of eight promising pavement performance measures highway agencies can use as leading indicators for long-term investment strategizing and decisionmaking and two promising transportation asset management methodologies (TAMMs). In phase II, the promising performance measures and a proposed TAMM were analyzed at the State level to validate their use. Phase II also sought to validate performance measures at the Federal level. This detailed piloting and demonstration effort also produced valuable insight and guidance in support of implementing the measures and TAMM.

RESEARCH OBJECTIVES

Phase II of this research project included the following three objectives:

1. Develop, test, and validate the promising NGPPMs from the phase I findings through pilot implementation.
2. Develop, test, and validate the promising TAMMs from phase I through pilot implementation to enable full implementation of a comprehensive asset management plan. (This process included finding common ground for tradeoff analysis of disparate assets that are traditionally assessed and managed individually).
3. Develop suggestions on modifying existing asset management systems to better support the use of a broad range of performance measures and allow agencies to dynamically conduct cross-asset tradeoff analysis for subsequent years. This dynamic analysis will provide optimal solutions that can be applied throughout the analysis period.

This final report describes the methodology used to complete each of these three objectives and presents the findings, conclusions, and implementation considerations that resulted.

RESEARCH APPROACH

To accomplish these objectives, the study team organized phase II into the following tasks and subtasks:

Task 1: Kick-Off Meeting With Project Panel

This task provided the opportunity to begin the collaborative process that continued throughout the study's duration. The research team and FHWA discussed the work plan, established the task structure, reviewed the delivery schedule, delineated roles and responsibilities, established communication protocols to ensure that all stakeholders were aligned, and created clear project expectations.

Task 2: Prevalidation Activities

This task was divided into three subtasks, as follows:

- Task 2.1: Develop NGPPMs. This task identified and evaluated the performance measures that best met the overarching objective of transportation asset management (TAM).
- Task 2.2: Develop asset management methodologies. This task combined the two methodologies selected in phase I and identified additional performance measures, data needs, and analysis capabilities to support the cross-asset analysis incorporated into the methodology.

- Task 2.3: Select States for validation effort. This task used the information from task 2.1 and task 2.2 to identify the State highway agencies (SHAs) most suitable for successfully validating the NGPPMs and proposed TAMM. The team made the selections at various times between February 2019 and April 2021 and included a formal rating process to determine the suitability of candidate States. The agencies selected included the Idaho Transportation Department (ITD), the South Dakota Department of Transportation (SDDOT), and the Texas DOT (TxDOT).

Task 3: Validation at the State Level

This task consisted of testing and substantiating the NGPPMs, proposed TAMM, and supporting tools and algorithms with the three selected State DOTs. The team carried out each validation effort as an individual subtask, as follows:

- Task 3.1: Idaho validation.
- Task 3.2: South Dakota validation.
- Task 3.3: Texas validation.

Task 4: Validation at the Federal Level

This task assessed the NGPPMs using data from the Highway Performance Monitoring System (HPMS) (FHWA 2016). The task used national-level pavement performance models that were developed based on the AASHTOWare® Pavement ME [mechanistic-empirical] Design software and are used in the Highway Economic Requirements System (HERS) software (AASHTO 2022; FHWA 2005).

Task 5: Revise Algorithms and Develop Final Recommendations and Procedures

This task involved development and documentation of final suggestions for the NGPPMs and proposed TAMM and the lessons learned from the validation efforts.

Task 6: Develop Guidance To Modify Management Systems for NGPPMs and TAMM

In this task, the research team developed guidance for accommodating the new performance measures into existing pavement management systems (PMSs) and bridge management systems (BMSs).

Task 7: Develop Dissemination Materials and Final Report

In this task, the research team developed three draft products to disseminate the results from phase II: this final report, a webinar presentation to promote the research findings, and two technical briefs (Ram et al. 2023; Thompson et al. 2023).

Task 8: Develop Final Versions of All Materials

This task included final versions of the three products, based on FHWA review comments of the draft versions prepared under task 7.

In addition to the completion of the tasks listed above, the research team submitted quarterly progress reports to the FHWA panel to document progress and identify any issues that arose.

REPORT ORGANIZATION

This report consists of nine chapters and nine appendices, as follows:

- Chapter 1: Introduction. This chapter provides an overview of the project by summarizing the project background, objectives, and research approach.

- Chapter 2: NGPPMs. This chapter discusses how the NGPPMs were identified and describes the methodology used to evaluate and develop them further.

- Chapter 3: Proposed TAMM. This chapter discusses how the proposed TAMM was developed and describes the supporting tools and framework deemed necessary to validate the methodology.

- Chapter 4: State validation planning. This chapter presents the validation objectives and basic approaches used to validate the NGPPMs and proposed TAMM at the State level. It also describes the evaluation and selection of State DOTs for State validation efforts.

- Chapter 5 through chapter 7: State validation results. These chapters present the results of the Idaho, South Dakota, and Texas validation studies, respectively.

- Chapter 8: Federal validation study. This chapter presents the results of the Federal validation study.

- Chapter 9: Implementation approaches and suggested pavement management functionality improvements. This chapter discusses key aspects of implementing the NGPPMs and proposed TAMM, including strategies for practical use, suggestions to better support analysis, and the benefits of implementation.

- Chapter 10: Findings and conclusions. This chapter presents important findings and conclusions about the suitability and effectiveness of the NGPPMs and proposed TAMM based on the validation efforts undertaken in the study.

- Appendix A: State validation interview questions. This appendix lists all the interview questions provided to a select number of State agencies as part of the initial State agency selection process.

- Appendices B–D: Detailed workplans for State validations. These appendices detail the process and schedule used to conduct the Idaho, South Dakota, and Texas validation studies, respectively.

- Appendix E: Compatible performance computations in management systems. This appendix provides technical detail on the calculation of parameters within PMSs and BMSs as inputs to the tradeoff analysis for multiasset performance objectives (TA-MAPO) spreadsheet tool.

- Appendices F–H: State validation technical memos. These appendices provide summaries of the Idaho, South Dakota, and Texas validation efforts, respectively and present the implementation plans developed for each agency.

- Appendix I: TA-MAPO. This appendix describes the layout and functionality of the TA-MAPO tool.

CHAPTER 2. NEXT-GENERATION PAVEMENT PERFORMANCE MEASURES

BACKGROUND AND OBJECTIVES

Phase I of the NGPPM study resulted in the identification of eight promising performance measures, which can be used by highway agencies as leading indicators for long-term investment strategizing and decisionmaking. The measures consisted of three lifecycle measures and five financial measures, as follows:

- Lifecycle performance measures:
  - Remaining service interval (RSI) (Elkins et al. 2013).
  - Annualized unit cost ratio (AUCR) (also known as annualized cost per lane-mile (ACLM)).[5]
  - Cost accrual ratio (CAR).[6]

- Financial performance measures:
  - Asset sustainability index (ASI) (Proctor, Varma, and Varnedoe 2012).
  - Asset sustainability ratio (ASR) (Ram et al. 2023).
  - Asset consumption ratio (ACR) (Ram et al. 2023).
  - Stewardship liability ratio (SLR), formerly known as backlog reduction ratio (BRR) (Ram et al. 2023).
  - Simple option cost (SOC).[7]

Lifecycle performance measures characterize and monetize the long-term investment strategies (construction, maintenance, and rehabilitation treatments) associated with providing a desired level of service (LOS) for a highway asset. These measures encourage activities that reduce the long-term cost of system preservation.[8] Thus, their focus is on the evaluation of strategy cost-effectiveness and achieving the desired overall system performance at the lowest practicable lifecycle cost (LCC).

Financial performance measures indicate if an adequate level of investment is being made to offset the rate of asset depreciation. These metrics encourage a long-term, TAM-based approach to managing infrastructure—not just to meet condition targets today, but to sustain those targets into the future. Because their units of measure are consistent, financial metrics can be compared across asset classes.

FHWA selected each of the above performance measures for detailed evaluation and development in phase II. The objective of the detailed evaluation was to evaluate the eight selected performance measures, identify those that best met the overarching objective of TAM

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[5] Sadasivam and Mallela. 2017. *Identification of Effective. . .Volume 1: Pavement Performance Measures*.

[6] Sadasivam and Mallela. 2017. *Identification of Effective. . .Volume 1: Pavement Performance Measures*.

[7] Bryce, J., G. Rada, S. Van Hecke, and J. Zissman. 2016. *Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements*. Draft final report. Unpublished. Washington, DC: Federal Highway Administration.

[8] In this report, the use of the term “preservation” or “system preservation” refers to a broad set of actions performed for upkeep and maintenance of the asset. These actions may include maintenance, preservation (preventive maintenance), rehabilitation, and reconstruction/renewal/replacement.

(i.e., maintaining assets in a SOGR at the minimum practical LCC), and develop candidate measures sufficiently for the planned State- and Federal-level validation efforts.

METHODOLOGY

The process used to evaluate and develop performance measures consisted of four steps: feasibility assessment, data needs assessment, use case assessment, and performance measure calculation. The desirable qualities for the validation-ready measures were that they be leading and process-oriented, comparable across multiple asset classes, unitless or consistent units across asset classes, and predictable. Although the team hoped that the measures would be applicable to a broad range of asset classes, this application was not a requirement—nor was it expected, given the separate management practices historically been used for each asset class. Therefore, the evaluation and methodology were conducted from a pavement perspective, but the process is expected to be applicable to other asset classes with minor adjustments.

Feasibility Assessment

The research team accessed the following factors to determine the feasibility and suitability of each measure for implementation at the State and Federal levels:

- Stakeholder concerns: Relevant issues, including asset condition, LOS, long-term cost, safety, and mobility were measured and addressed.
- Action-oriented characteristics: These characteristics include types of business decisions that different agency management levels can make with measures, such as strategic (for agency executives and upper management), tactical (for asset managers), and operational (for asset engineers and practitioners). They can also include types of business decisions that can be made with measures at different highway system levels (statewide network, districtwide network, project). Additionally, they can include the level of importance in decisionmaking (i.e., intermediate decisions leading to additional analyses versus final decisions generating direct action). The team also conducted an assessment to determine whether measures could be used as leading or lagging indicators.
- Intuitiveness: This factor resonates among various decisionmakers and can be easily understood.
- Appropriateness and comprehensiveness: The measure captures the right information for making decisions and considers all significant factors and features.
- Statistical reliability: The measure generates repeatable and accurate results with small margins of error.
- Quantifiable results: The measure calculates, aggregates, and compares to other results with ease.
- Verifiable outcomes: The measure provides measure outcomes that can be audited or evaluated with relative ease.

- Adaptability: The measure incorporates into pavement, bridge, or other asset management systems.
- Implementation readiness: The measure implements easily, with minimal additional data collection or mining required and minimal costs to implement.

Data Needs Assessment

Each measure was evaluated for the following data issues:

- Data needed at the State and Federal levels.
- Data availability and readiness.
- Data alternatives, including the ability to collect required or surrogate data to enable calculation of the measure and the relative magnitude of additional data collection costs.
- Data quality, including the completeness, reliability, and variability of the data.
- Data sources, including pavement, bridge, and other management systems containing historical condition information; asset performance models; treatment costs; and treatment decision criteria and rules.

Use Case Assessment

The applicability of each measure for the following TAM use cases (described in detail in chapter 3) was examined as follows:

- Funding and policy determination (network level).
- Need criteria or warrants (network and project level).
- Resource allocation (network level).
- Performance targets (network level).
- Future performance forecasts (asset and network level).
- Project development (project level).
- Priority programming (network, program, and asset levels).

Performance Measure Calculation

The methods needed to calculate each performance measure using the data identified in step 2 were developed and documented.

LIFECYCLE PERFORMANCE MEASURES

Lifecycle performance measures are significant to an agency when evaluating the consequences of short- and long-term funding shortfalls and suboptimal treatment actions associated with a proposed lifecycle strategy under constrained budget situations. Table 1 provides an overview of the lifecycle performance measures.

Table 1. Overview of lifecycle performance measures.

Measure	Description	Source
RSI	Based on identifying a structured sequence of the type and timing of various intensities of repair and replacement actions required to provide the desired LOSs to users over the asset lifecycle at minimum practicable costs (figure 1). Provides a framework to incorporate a whole life perspective in determining future repair and replacement actions (i.e., considering both current condition and past actions in determining future actions, performance risks, and investment needs).	Rada et al. (2016) FHWA (2017)[9]
AUCR	Calculates ratio of the annualized cost of all planned expenditures over the pavement lifecycle to the annualized cost of expenditures under the optimized strategy. Compares planned investments to the optimized lifecycle strategy.	FHWA (2017)[10]
CAR	Calculates ratio of NPV of all programmed costs over a chosen time against the NPV of the agency's optimized LCP. Compares the actual investments made to date against the optimized lifecycle strategy that requires the minimum practicable LCCs.	FHWA (2017)[11]

LCP = lifecycle planning; NPV = net present value.

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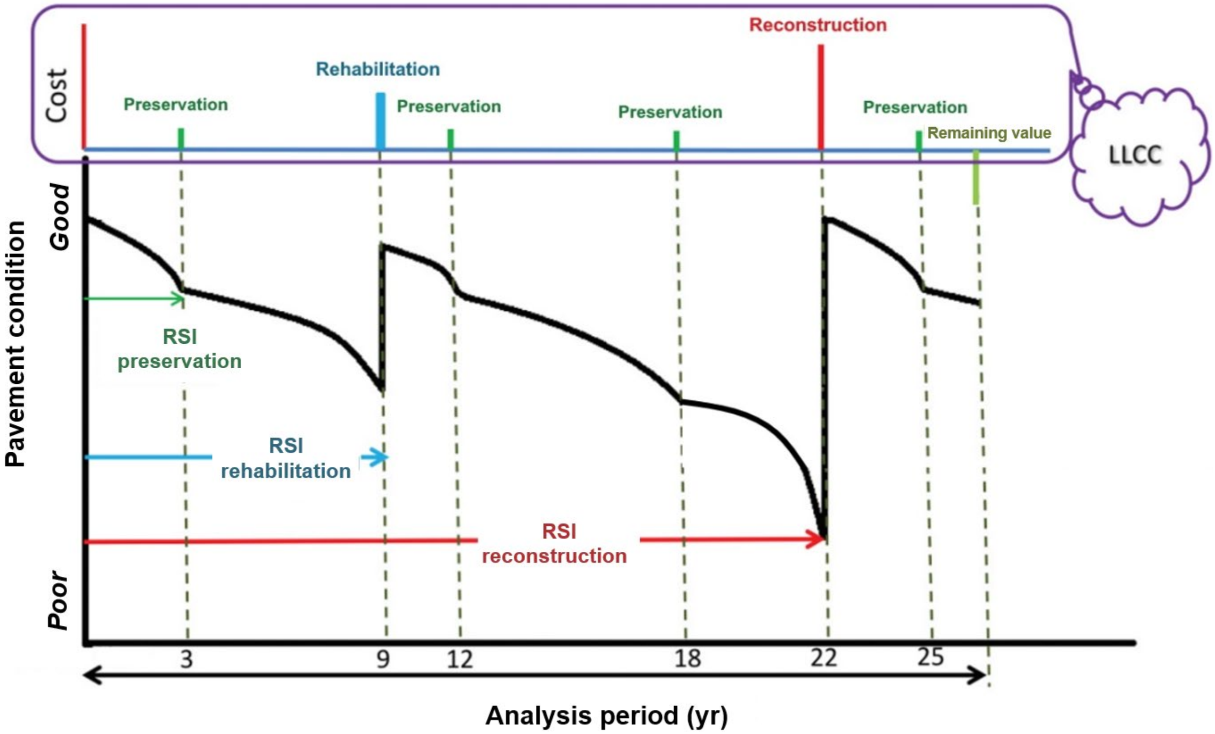
[9] Bryce, Rada, Van Hecke, and Zissman. 2016. *Identification of Effective*.

[10] Sadasivam and Mallela. *Identification of Effective. . .Volume 1: Pavement Performance Measures*.

[11] Sadasivam and Mallela. *Identification of Effective. . .Volume 1: Pavement Performance Measures*.



Source: FHWA.
LLCC = lowest lifecycle cost.

Figure 1. Graph. Illustration of pavement RSI (modified from Rada et al. 2016).

Remaining Service Interval

RSI is a pavement lifecycle management framework rather than a direct tangible performance measure. The RSI analysis framework uses the following strategies (Ram et al. 2020):

- Performance indicator(s) (either lagging or leading).
- Established performance prediction models (both performance deterioration and performance jump).
- Established treatment rules (to eliminate unrealistic or infeasible treatment sequences).
- Lifecycle costing techniques (to generate multiple feasible long-term pavement strategies).

Each strategy is defined by a series of treatments (preservation, rehabilitation, or reconstruction) that keep pavement conditions at desired performance levels over a selected analysis period. The output from the analysis is a combination of optimal and suboptimal treatment strategies. These strategies include the sequence of treatments and the associated LCC for all feasible treatment strategies that can be used to determine the lowest practical network-level LCC for managing a pavement network based on established budget constraints (Ram et al. 2020).

Feasibility Assessment

In the report titled *Reformulated Pavement Remaining Service Life Framework*, Elkins et al. (2013) describe developing RSI (as part of the project titled Definition and Determination of Remaining Service and Structural Life) specifically for pavements. The RSI concept was developed to address ambiguity caused by widely varying meanings assigned to different forms of remaining service life (RSL) terminology (Rada et al. 2016). The RSI is a forward-looking measure that uses lagging or leading performance indicators (or both) and associated performance models to describe the future repair and replacement needs of a pavement. The RSI provides a comprehensive picture of the future long-term activities that will keep conditions at acceptable levels at some associated LCC. The measure is somewhat action-oriented and intuitive and is ready for implementation.

Data Needs Assessment

In general, much of the data needed for lagging performance indicators are available. Many of the models needed for predicting future condition/performance and defining the performance jump (i.e., immediate condition/performance impact) of treatments that are applied are also available. Several States would need to collect network-level friction data to make friction part of the performance indicators used to identify future repair and replacement activities.

The data and models associated with leading performance indicators are only partly available. Researchers in the field of pavement engineering have performed a substantial amount of testing using traffic speed deflection devices (TSDDs) in recent years, in addition to research into the development of structural capacity measures based on TSDD deflections. However, more work is required to better model structural performance and, in turn, identify structural treatment types and timings for use in RSI. That said, State highway agencies are beginning to implement TSDD performance measures in pavement management.

Use Case Assessment

The RSI measure is applicable to many of the use cases, including those related to network-level prioritization, optimization, lifecycle planning, and program development.

Performance Measure Calculation

The process for performing the RSI evaluation and calculating the LCCs of alternative strategies is as follows:

1. Determine the specific performance indicators (distresses, distress indexes, structural characteristics, surface characteristics, etc.) that will be used to guide the development of treatment strategies.

2. Identify the preservation, rehabilitation, and reconstruction treatments to be considered and categorize them accordingly. Also, develop updated costs for each treatment.

3. Identify the LOS threshold levels for pavement smoothness and safety, which are performance indicators that impact road users. (Note: Threshold levels may or may not function as treatment triggers; a treatment can be applied at any time before the threshold condition is reached).

4. Develop or identify the deterioration and performance-jump performance models to be used for each treatment. These models will take into consideration or be responsive (if possible) to the pretreatment condition of the pavement to which the treatment is applied.

5. Define the analysis period (typically 30 years or more) and discount rate to be used for conducting the lifecycle cost analysis (LCCA) (FHWA 1998). Determine how remaining value (RV) at the end of the analysis period, if applicable, will be computed.

6. Compute the LCCs for the alternative pavement strategies.

To apply RDI, multiple pavement strategies are identified, each with a structured sequence of preservation, rehabilitation, and reconstruction treatments (or, alternatively, preservation, light rehabilitation, and heavy rehabilitation treatments). This structured sequence will satisfy the desired performance levels. Next, the LCC of each strategy is calculated based on the timings and costs of the treatments and the selected discount rate. FHWA developed a white paper that clearly and simply communicates the RSI measure and its application at the project and network levels (Ram et al. 2020).

Annualized Unit Cost Ratio

Although this performance measure (as currently defined) is specific to pavements, it can be customized for other types of assets if the functional unit of the measure is changed from “lane-mile” to a “unit” quantity of an asset. The functional unit may take various forms depending on asset type. For example, “per bridge” or “per deck area” could be the functional unit for bridges; “per unit asset” could be the functional unit for assets that are maintained as individual entities such as closed-circuit television (CCTV) cameras and sign structures.

Feasibility Assessment

Overall, the AUCR is relatively simple to compute and can be easily incorporated into a PMS. Additionally, the measure is expected be intuitive to decisionmakers. On the other hand, because the AUCR is not directly tied to pavement conditions, LOSs, and other stakeholder concerns, it may not portray a consistent performance level and thereby yield significant variability in cost over time. As a result, the measure may not accurately inform decisionmakers whether the optimal lifecycle strategy is being implemented and followed or the consequences of deviations from the optimal lifecycle strategy in any terms other than cost.

The AUCR measure is presented as a ratio of the programmed annualized unit cost to the unit cost of the optimized lifecycle strategy. The optimized annualized unit cost is the unit cost of the optimal lifecycle strategy for the asset when budget constraints are not applied. The programmed annualized unit cost is based on what the management system anticipates that the selected lifecycle strategy will incur, considering the agency’s budget constraints. An agency’s ability to compute the AUCR depends on how advanced the agency’s management systems are. However, if the agency can compute the measure, it can be used to generate time-series trends that will help in planning future treatments more effectively. Notably, the measure does not consider any historical treatments and costs. The current condition state of the asset is assumed to be the starting point for the analysis.

Overall, the success of the measure will depend on the rules and regulations in place, the agency’s culture, the agency’s ability to track costs effectively, and the final form of the measure that is selected. Acquiring the necessary data and implementing the measure into management systems may take significant effort. However, agencies are likely to already be prepared to implement the measure, and they stand to benefit greatly from it.

Data Needs Assessment

To develop an optimized lifecycle strategy, agencies need to program performance prediction models, treatment strategies, cycles, and costs into their PMSs and BMSs. Most agencies do not have all these data elements programmed into these systems, so their systems may generate suboptimal strategies. The AUCR has the potential to help agencies develop an optimized strategy, and the process—due to its simplicity—is not costly. Also, the agencies already have the data needed.

The largest challenge with the AUCR measure is that it does not inform an agency if they are following their optimized lifecycle strategy. Using the AUCR measure, an agency may possibly have an annualized cost that matches the optimized annualized cost as the agency adopts strategies that are not in the optimal lifecycle strategy. To rectify this issue, this measure needs to be used in conjunction with a condition-based performance measure.

Use Case Assessment

The AUCR measure is project-level driven but has some network-level applications. Although the AUCR has potential relevance to several of the use cases, its usefulness may be hindered by significant year-to-year variations in cost. Therefore, future agency efforts should be directed toward measuring actual treatment costs to improve the accuracy of pavement management analyses.

Performance Measure Calculation

The equivalent uniform annual cost (EUAC) is a calculation that converts a time stream of costs and benefits into annualized present-value dollars over the lifecycle of the asset.[12] EUAC is calculated using the following equation:

$$EUAC = NPV\left(\frac{r(1+r)^N}{(1+r)^N-1}\right) \quad (1)$$

Where:

r = discount rate.
N = analysis period.
NPV = net present value.

$$AUCR = \frac{EUAC_{programmed}}{EUAC_{optimized}} \quad (2)$$

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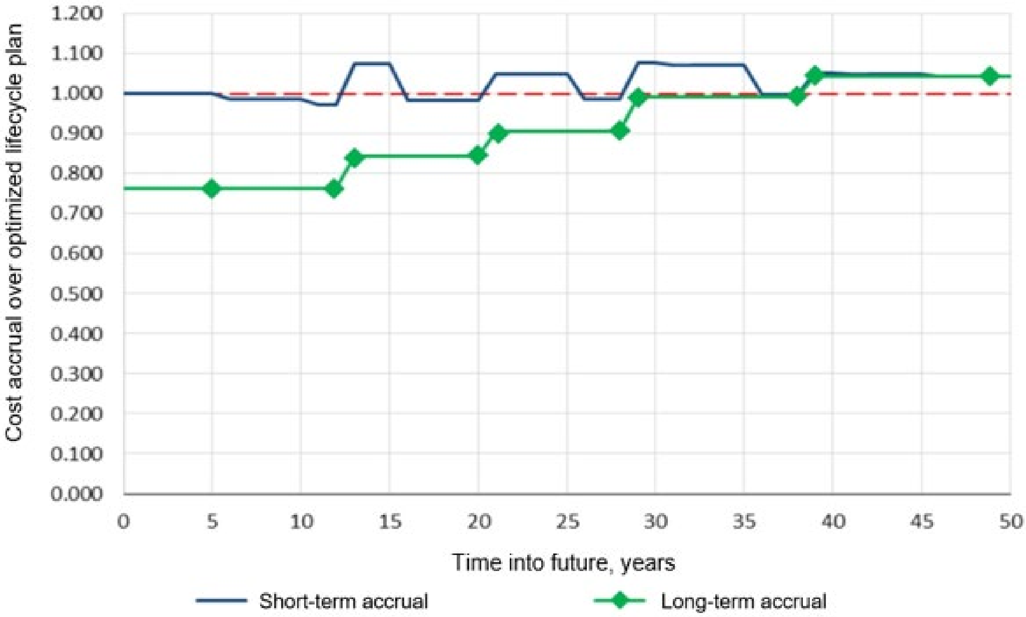
[12] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.

Cost Accrual Ratio

The CAR can be calculated and tracked using two approaches, described as follows and illustrated in figure 2.[13]

- Short-term accrual: This approach compares the net present value (NPV) of costs programmed over a chosen time to the corresponding NPV of the costs budgeted in the agency's optimized lifecycle strategy at the same time point.
- Long-term accrual: This method compares the NPV programmed over a chosen time horizon to a single overall NPV of the agency's optimized lifecycle strategy.



Source: FHWA.

Figure 2. Graph. Example comparing short-term and long-term CAR approaches.

A CAR greater than one indicates missed opportunities in optimal lifecycle management of an asset. Notably, a CAR less than or equal to one does not necessarily mean the actual lifecycle strategy matches the optimal lifecycle strategy. A CAR can be less than or equal to one for a variety of reasons, such as lifecycle management efficiencies, the use of high-performance materials and improved construction practices, and the underutilization of assets. To mitigate variability, the accruals of investments are normalized to a single NPV of the agency's optimized lifecycle strategy. The use of a single NPV for normalization helps to communicate how costs accrue over the analysis period and captures any differences that may occur due to factors related to an agency's lifecycle planning (LCP) and funding practices.

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[13] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures.*

Feasibility Assessment

Even through the CAR can be used as a leading or lagging measure, it may be a more feasible performance measure if it is focused on the asset-related costs covered in the agency's TAMP and incorporates those costs into the agency's management systems. This process can be done by comparing the agency's committed costs in TAMPs against the agency's actual costs at the network level. However, determining the network-level costs that led to improved conditions may still be a difficult task for agencies. Thus, the CAR might be a more practical performance measure if its focus in TAMPs is on preservation costs rather than on including all asset-related costs. This consideration is particularly important for pavements, as other assets are often improved or worked on during a pavement project (e.g., pavement striping, guard rails, and signs). A degree of severity needs to be defined for the measure so that different ratio values can communicate meaning.

Overall, the feasibility study shows that most agencies can implement the CAR as a performance measure and are anticipated to benefit from its use. The CAR has the potential to help agencies determine if they are on track in meeting their optimal lifecycle strategy targets. If an agency is not on track, the measure can serve to identify long-term process changes that might be needed to improve treatment effectiveness.

Data Needs Assessment

An optimized lifecycle strategy should consider all planned costs to maintain the asset in serviceable conditions during its lifecycle. The measure does not consider any historical treatment actions. The current condition state of the asset is assumed to be the starting point for the analysis. Where appropriate, especially when the asset fails to provide the desired LOSs, all user costs (e.g., travel delay costs, vehicle operating costs, crash costs, environmental costs) should be considered.

Not all agencies have an established optimized lifecycle strategy that includes all these factors as described. If an agency does not have such a strategy, it will need to improve its optimized strategy process to calculate the CAR. Given the uncertainties associated with long-term costs, one way an agency can improve its optimized strategy process is by adjusting its LCCs to account for the influence of exogenous factors, such as construction price inflation, traffic, and resilience needs. Another way to improve this process is by setting a project-level-based threshold (e.g., the IRI (international roughness index)) to compare actual performance to optimal performance.

Use Case Assessment

Like the AUCR measure, the CAR is project-level driven, but it has some network-level applications. Also, like the AUCR, the CAR has potential relevance to several of the use cases. However, the CAR compares future costs with past costs, so it is probably a more time-stable measure than the AUCR, which makes its potential relevance with the use cases stronger.

Performance Measure Calculation

The CAR is tracked by comparing the NPV of costs incurred over a chosen time horizon to the NPV of the agency's optimized lifecycle strategy. Meanwhile, NPV is a calculation that converts all programmed costs and benefits into present dollars. NPV is calculated using the following equation:

$$NPV_{programmed} = \sum Programmed\ Treatment\ Costs \times \left(\frac{1}{(1+r)^n}\right) \tag{3}$$

Where:

r = Discount rate to account for the time value of money.
n = Number of years when the cost will be incurred.

$$Short - Term\ CAR = \frac{NPV_{\ planned\ costs\ to\ date}}{NPV_{all\ costs\ in\ optimized\ strategy\ to\ date}} \tag{4}$$

$$Long - Term\ CAR = \frac{NPV_{\ planned\ costs\ to\ date}}{Overall\ NPV_{all\ costs\ in\ optimized\ strategy}} \tag{5}$$

FINANCIAL PERFORMANCE MEASURES

The financial measures discussed in this chapter are intended to be used to make sound long-term investment decisions in conjunction with condition-based metrics (e.g., IRI, cracking, and rutting for pavements; National Bridge Inventory (NBI) condition ratings for bridges) and lifecycle measures (CFR 2017b; FHWA 2023). Table 2 provides an overview of the financial performance measures.

Table 2. Overview of financial performance measures.

Measure	Description	Source
ASI	Ratio of budget allocated to amount needed to address all current management system treatment selections. Helps decisionmakers determine the adequacy of investments to address needs identified by the management system. Trends in the ASI can help agencies determine a strategic investment plan.	Proctor, Varma, and Varnedoe (2012)
ASR	Ratio of asset maintenance, preservation, and replacement expenditure to asset depreciation for a given time. Focuses on the process that is expected to drive pavement condition. Helps decisionmakers determine if sufficient investments have been made in the current time.	Ram et. al (2023)
ACR	Ratio of depreciated asset replacement cost to current replacement value. Metric highlights average proportion of as-new/as-built condition left. Trends will show if adequate resources are being invested to maintain current life expectancy.	Howard, Dixon, and Comrie (2011)
SLR (formerly BRR)	Ratio of unfunded treatment needs to replacement cost of the network. Can be used to compare treatment strategies. Applies to multiple assets, so the application capability exists to conduct tradeoff analysis and compare the impact of different funding levels across asset classes.	FHWA (2017)[14]
SOC	Estimates difference in costs for two different scenarios for a single pavement section and ratio of saved costs to deferred costs for a pavement network. Provides immediate feedback regarding the decision to fund specific pavement segments and information about which pavement segments are resilient to decreased funding over the lifecycle. This metric is not recommended for further evaluation due to the complexities associated with calculating the SOC for a large network and because the SOC is not particularly intuitive for decisionmaking.	FHWA (2017)[15]

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[14] Zimmerman, Allen, Ram, Duncan, Smadi, Smith, Manda, and Bektas. 2016. *Identification of Effective*.

[15] Bryce, Rada, Van Hecke, and Zissman. *Identification of Effective*.

Asset Sustainability Index

Feasibility Assessment

The ASI is a relatively simple measure that can easily be incorporated into an agency's existing business processes. The ASI can be used as both a leading indicator (when comparing planned investments to an optimized plan) and a lagging indicator (when comparing actual investments to a previously determined spending plan). When used as a leading indicator, the ASI can help in the financial planning process to ensure that investments being made are financially sustainable over the long term. When used as a lagging indicator, historical ASI trends can help agencies evaluate the effectiveness of the investment strategies adopted by the agency and drive business process changes, when warranted (Proctor, Varma, and Varnedoe 2012).

Data Needs Assessment

For each network subgroup (e.g., NHS, non-NHS, interstates) and investment category (maintenance, preservation, rehabilitation, and reconstruction) that the agency wishes to monitor using the ASI, the following data are required for each year in the analysis period:

- Condition performance models (IRI, rutting, cracking, etc.), treatment strategies, and treatment costs (assumed to be available from management systems).
- Budget needs informed by the management system.
- Amount allocated for needs determined through the agency's financial planning process, accounting for expected revenues adjusted for inflation.

Use Case Assessment

The ASI is a network-level measure and is more relevant to the following use cases:

- Resource allocation at the network level.
- Performance target establishment at the network level for various investment categories (such as maintenance, preservation, rehabilitation, and reconstruction).

The ASI can be used for almost any type of asset, as it is generic in nature. The ASI cannot be used as a standalone measure to monitor asset performance and investment needs. However, when used in conjunction with traditional condition-based performance indicators and other lifecycle measures, it can help to guide where an agency should be making its investments to minimize the network-level LCCs.

Performance Measure Calculation

The ASI is calculated simply, by dividing the amount budgeted by the amount needed to address the optimized treatments generated by the management system. It can be calculated on an annual basis or for a particular budget cycle or planning period.

$$ASI = \frac{Amount\ Budgeted}{Amount\ Needed} \tag{6}$$

However, determining the amount needed can be a complex process. Following are the key considerations involved (Proctor, Varma, and Varnedoe 2012):

- Annual investment needs are typically based on a lowest LCC approach that includes a combination of maintenance, preservation, rehabilitation, and replacement activities at appropriate timings over the lifecycle of an asset.
- The denominator can only include the needs for maintaining and preserving the existing network and does not account for network expansion.
- Special situations are typically excluded from ASI calculations (e.g., large historic bridges, which are managed using a different approach).

The "amount budgeted" typically comes from the agency's financial planning process. Agencies will want to develop financial plans that span a duration of at least 6 years for this measure to be effective in the decisionmaking process.

Asset Sustainability Ratio

Feasibility Assessment

The ASR is a network-level measure, and like the ASI, submeasures can be defined for different portions of the network or different investment categories. The ASR can be used as both a leading indicator (when comparing planned expenditures to projected asset value depreciation) or a lagging indicator (when comparing actual expenditures to actual depreciation).

When used as a leading indicator, the ASR indicates if the agency is making adequate investments to offset the asset value depreciation over the analysis period. When used as a lagging indicator, time-series ASR data can be used to improve depreciation models and even develop ASR-based performance models that can be used in the financial planning process.

Although the ASR is a relatively simple measure to calculate and understand, a few agencies may experience some challenges in estimating asset value depreciation for various asset classes. To start implementing the measure, agencies may choose to adopt simplified approaches to model depreciation; as their processes and capabilities mature over time, they may choose to adopt more sophisticated depreciation models.

Data Needs Assessment

For each network subgroup (e.g., NHS, non-NHS, interstates) and investment category (maintenance, preservation, rehabilitation, or reconstruction) an agency wishes to monitor using the ASR, the following data are required for each year in the analysis period:

- Condition performance models (IRI, rutting, cracking, etc.), treatment strategies, and treatment costs (assumed to be available from management systems).

- Asset maintenance, preservation, rehabilitation, and reconstruction expenditures.

- Annual asset value depreciation.

Use Case Assessment

The ASR is a network-level measure applicable to the following use cases (Ram et al. 2023):

- Determining funding at the network level.
- Establishing performance targets at the network level based on asset age categories.

The ASR is a generic measure, and it can be applied to a wide array of asset classes as long as age/condition and depreciation models are available.

The primary use of this measure is to determine if an agency is dedicating adequate funding to offset the asset depreciation over time. This measure can be used in conjunction with the lifecycle measures discussed in the previous section to determine the optimum time for investing in the assets to achieve the lowest practical LCCs. When asset portfolios are relatively young, the ASR values can be lower than 50 percent. When asset portfolios have matured, the values may be greater than 100 percent—depending on the type of asset and the required level of investment (Howard, Dixon, and Comrie 2011).

Performance Measure Calculation

ASR is the ratio of the asset renewal and replacement expenditure relative to the depreciation for a given period. It measures whether an agency is investing in maintaining the value of the assets at the rate at which they are deteriorating (Ram et al. 2023).

$$ASR = \frac{Asset\ Renewal\ or\ Replacement\ Expenditure}{Asset\ Value\ Depreciation} \tag{7}$$

The asset renewal/replacement expenditures (or needs) can be a direct output from the management systems. Determining the depreciation in asset value can be a more challenging task. Agencies may not have established asset value depreciation models for the majority of the assets they are managing. Depreciation models will need to be developed to implement this measure. Several assumptions and expert judgment will be required to develop the first generation of depreciation models for various assets classes. As the management systems mature and when more data are available, sophisticated models that incorporate asset conditions, functional classes, and other parameters may be developed by agencies.

Asset Consumption Ratio

Feasibility Assessment

ACR is a leading indicator that is used to compare the projected depreciation in asset value to the estimated replacement value in the same period. Although the ACR is a relatively simple measure to calculate, agencies may occasionally experience some challenges in determining asset value depreciation for the various asset classes. The challenges associated with implementing the ACR are almost identical to those discussed in the ASR "Feasibility Assessment" section.

Data Needs Assessment

For each network subgroup (e.g., NHS, non-NHS, interstates) that the agency wishes to monitor using the ACR, the analysis requires the following data for each year in the analysis period:

- Condition performance models (IRI, rutting, cracking, etc.), treatment strategies, and treatment costs (assumed to be available from management systems).

- Current replacement value (CRV). (Unit costs for asset replacement from the agency's existing management systems can be leveraged.)

- Annual and cumulative asset value depreciation.

Use Case Assessment

The ACR is not generally applicable to any of the use cases, except in terms of setting performance targets at the network level. This measure is independent of asset type and can be easily used within an agency to monitor remaining as-built asset conditions, as long as accurate depreciation models and replacement cost data are available.

Performance Measure Calculation

The ACR is the ratio of the depreciated asset replacement cost divided by the current asset replacement cost. The measure is intended to be used for communication purposes, highlighting the aged condition of an agency's asset network. The ACR uses a financially depreciated value of replacement cost to approximate the relative RSL of an asset. This measure can be used on individual assets or on an asset class. Using financial depreciation techniques, the value of the asset may easily follow a linearly decreasing value over time, which could approximate the typical asset condition versus time curve.

$$ACR = \frac{Depreciated\ Replacement\ Cost}{Current\ Replacement\ Cost} \tag{8}$$

$$Depreciated\ Replacement\ Cost = Current\ Replacement\ Cost - Asset\ Value\ Depreciation \tag{9}$$

The challenges associated with calculating asset value depreciation and the development of depreciation models were described in the discussion on ASR. In addition to depreciation, the ACR also requires calculation of the current replacement cost. There are several approaches an agency may choose to adopt to compute the current replacement cost, summarized as follows:

- Use the unit costs in the management system used by the agency to estimate the replacement costs.

- Report the current asset replacement value in financial statements, so these data can be leveraged for ACR computations.

- Calculate the CRV for complex assets that involve multiple components, other ancillary assets, or both using several assumptions. For example, the removal and replacement of 1 mi of a pavement may require considering issues that including the following:

    - Culverts and drainage features to be replaced: amount.
    - Guardrail quantity to be replaced.
    - Shoulder type to be included in the new design.
    - Pavement marking and raised pavement markers.
    - Lighting structures.

    Each individual pavement segment is a unique entity and will have a unique replacement cost associated with it. However, for the ACR calculation, drilling down to each detail can be time consuming and thus is not feasible. Historical agency bid tabulations can be analyzed to establish the fraction of replacement costs by asset class that is devoted to the replacement of ancillary assets.

Another key issue of note is that the ACR significantly depends on the asset age/condition. As asset age increases and conditions deteriorate, ACR will gradually reduce over time. For assets that are not managed based on their condition (such as CCTV cameras that are generally replaced when they fail), the ACR values are generally not particularly meaningful at the project level.

Stewardship Liability Ratio

Another common characteristic of an agency's asset management program is backlog. Backlog is a calculation of the total cost of treatment needs that have been deferred due to budget constraints. The SLR (originally referred to as the BRR) is a network-level measure to monitor and track the backlog that is being addressed during any fiscal period relative to the replacement value of the pavement network.

Feasibility Assessment

The SLR can be used as either a leading or a lagging measure. For the SLR to be used as a leading indicator, the agency should have a reliable estimate of the anticipated future funding level and a good handle on the treatments that will be programmed. If an agency simply intends to track the treatment needs on an annual basis and compare them to the needs that were actually addressed, the SLR can be used as an internal performance measure to track the annual volume of backlog. Additionally, time-series trends can help in analyzing whether the asset management strategy adopted by the agency has been effective or changes are required to the business processes.

The SLR is a simple measure to calculate; however, a common definition of the term "backlog" is required to ensure agency-wide consistency. It may be useful to define submeasures ("preservation backlog," "rehabilitation backlog," etc.) due to the dynamic nature of the performance measure.

Data Needs Assessment

For each network subgroup (e.g., NHS, non-NHS, interstates) and investment category (maintenance, preservation, rehabilitation, and reconstruction) that an agency wishes to monitor using the ASI, the following data are required for each year in the analysis period:

- Condition performance models (IRI, rutting, cracking, etc.), treatment strategies, and treatment costs (assumed to be available from management systems).
- Required funding to address the total needs identified.
- Committed funding to address the total needs identified.

The data needs for computing the SLR and the ACR are the same; hence, computing the SLR should require minimal effort once a procedure has been established for the ASI and ACR.

Use Case Assessment

The SLR can be used for resource allocation at the network level. When used as a leading measure, the time-series trends in the SLR for various investment categories (e.g., maintenance, preservation, rehabilitation) can be used to determine adjustments to the investment allocations. These allocations can help in visualizing areas where backlogs keep growing over time and indicate adjustments that asset LCP strategies adopted by the agency require.

Since this measure was developed during phase I specifically for this study, it has not been tested using actual data from transportation agencies. The discussions with the pilot test agencies may shed light on other potential uses for this measure.

Performance Measure Calculation

Although the data needs for this measure are mainly the same as the data needs for the ASI and ACR, a difference exists in the way this measure is calculated and presented. The SLR looks at the relative changes in the backlog compared to the replacement value of the pavement network. The measure inherently assumes that the agency will not be able to address all the needs identified, which is reasonable given that most transportation agencies are struggling to make ends meet when it comes to keeping assets in a SOGR.

The calculation of the SLR is a three-step process, as follows:

1. Obtain information on the total needs (in various categories, such as maintenance, preservation, rehabilitation, etc.) and level of funding expected in each category. These data on investment needs can come from management system runs, and data on anticipated level of investment can come from the financial planning process.
2. Calculate annual backlog in the various investment categories defined. Backlog is simply the arithmetic difference between the total needs and funded needs.

$$Backlog\ (or\ Unfunded\ Treatment\ Needs) = Total\ Needs - Funded\ Needs \qquad (10)$$

3. Calculate SLR. The backlogs determined for the first year in the analysis period (year 0) are used as the benchmarks for the remaining years in the analysis period to calculate the

SLR. Since the first year in the analysis period (2019) is being used as the baseline, the SLRs are calculated starting from the second year in the analysis period.

$$SLR_{Year\ n} = \frac{Unfunded\ Treatments_{\ Year\ n}}{Replacement\ Cost} \tag{11}$$

An SLR of zero indicates that all the treatment needs are being funded, and a value of one indicates that the entire pavement network needs to be replaced. Again, agencies cannot reasonably be expected to fund all the treatment needs. Hence, agencies will need to establish a baseline value for this metric by determining the level of backlog that might be considered acceptable. Time-series plots of the SLR can help visualize the trends to investigate when the current level of funding might be inadequate to keep the backlog growth in check. The general trendline can also help in visualizing if the agency is making any progress in managing the backlog to the established baseline levels.

CHAPTER 3. PROPOSED TRANSPORTATION ASSET MANAGEMENT METHODOLOGY

This chapter focuses on the proposed TAMM, which can be viewed as a prioritization methodology. In this context, the measure involves forward-looking estimates of future performance that are intended to support data-driven, result-oriented planning processes involving all types of infrastructure assets. The methodology is data-driven because it is meant to compute forecasted parameters in a uniform way using standardized data. It is limited by the availability and quality of data. It is result-oriented in that it supports a style of decisionmaking that evaluates alternatives based on the future outcomes they are likely to produce, using data-driven models to forecast these outcomes.

The models discussed in this chapter rely on future condition forecasts, performance, and agency actions and their costs and effects. Forecasts of future actions are carefully described as selections, not recommendations. The models select actions based on an approximation of the types of actions a given set of policies is likely to produce, including a set that minimizes long-term costs. The models are meant for decision support, not decisionmaking. They help make data more useful but are just a subset of the important considerations in making TAM decisions.

BACKGROUND

Transportation agencies own, operate, and maintain a diverse infrastructure to support the provision of transportation services to the public. Pavements and bridges may be the most prominent elements of this infrastructure, but agencies also manage a variety of other physical assets, including tunnels, earthworks, drainage facilities, guardrails, traffic control devices, lighting, and buildings. Some agencies also manage air, marine, and rail transportation assets. All these asset classes work together to facilitate service to the public, but each asset class has its own technologies and specialized maintenance requirements. Additionally, the performance of each asset class affects the public in different ways.

Because of the specialized technologies and professional disciplines required to construct and maintain the various classes of physical assets, transportation agencies have traditionally managed them separately. Over time, each asset class has evolved its own conceptual frameworks, research concerns, training requirements, technical jargon, and performance metrics. These evolved features have helped the industry become more efficient and effective. However, they have also created difficulties, such as communication gaps and incompatibilities that hinder the management of the transportation network as a whole and the way it is perceived by the public and nontechnical stakeholders.

One goal of TAM has been to develop a new set of practices and tools that leverage the great strengths of the separate technical disciplines while enabling integrated management of the complete infrastructure network. One of the key innovations that has enhanced TAM in recent decades is the development of management systems. These systems take advantage of several new technologies, including computer hardware and software; standardized data collection methods; scientific understanding of physical deterioration processes; management's understanding of project delivery processes; and forecasting models for various aspects of performance, cost, and risk. All these technologies are continually evolving and improving, but they already show promise for improving the efficiency and effectiveness of the transportation system as a whole.

Characterizing Network Performance

Integrated management across asset classes involves several basic perspectives, including geographic (location and connectivity of network components); financial (common definitions of accounting and budgetary concepts); planning (strategic and long-range transportation plans); and management (human resources and administrative support). For the present study, the key integrating concept is network performance.

Managers of pavements, bridges, and other asset classes have developed many rigorous methods (based on science and technology) to assess the performance of individual assets. These methods are oriented mostly toward the selection of appropriate maintenance, preservation, and rehabilitation treatments; the estimation of costs; and the prioritization of investments within categories of work, responding to the needs of each asset class. Missing in the past was a framework for assessing the performance of the network as a tool for planning and prioritizing investments across asset classes in a way that responds to the needs of road users and stakeholders at large.

Fortunately, recent initiatives at the Federal and State levels have provided some key concepts that can organize this framework. MAP-21 documented a set of national performance goals in section 150(b) (U.S. Congress 2012). Many States have similarly documented their performance goals in State legislation or strategic plans. Common themes in many of these goal statements are maximizing safety, mobility (for people and freight), and environmental sustainability; minimizing long-term cost; and managing condition and risk.

Subsequent Federal rules in 23 CFR Part 490, Part 515, and Part 667 began the process of quantifying these goals, starting with condition. They also describe a set of processes and tools that transportation agencies are expected to implement that enable them to reliably quantify their network performance at any point in time, set performance objectives and targets, and develop investment plans that lead toward the accomplishment of these objectives and targets (CFR 2016a, 2021b, 2016b). Management system technology is envisioned as the means by which agencies can work with data on asset-level technical performance and investment plans to make reasonable and consistent forecasts of network performance. Transportation agencies are then able to plan investments that can be expected to accomplish network goals over a timeframe on the order of 10 years.

System Support of Business Needs

Management systems consist of data, software, models, and business processes that support asset management. They provide this support at multiple levels of detail for different purposes. Figure 3 shows how the analytical processes in the technical domain start with condition data and models of deterioration and treatments to yield forecasts of future conditions and costs. These forecasts then influence decisions about treatment selection and the delivery of infrastructure preservation.[16] These activities are largely specific to each asset class; the methods

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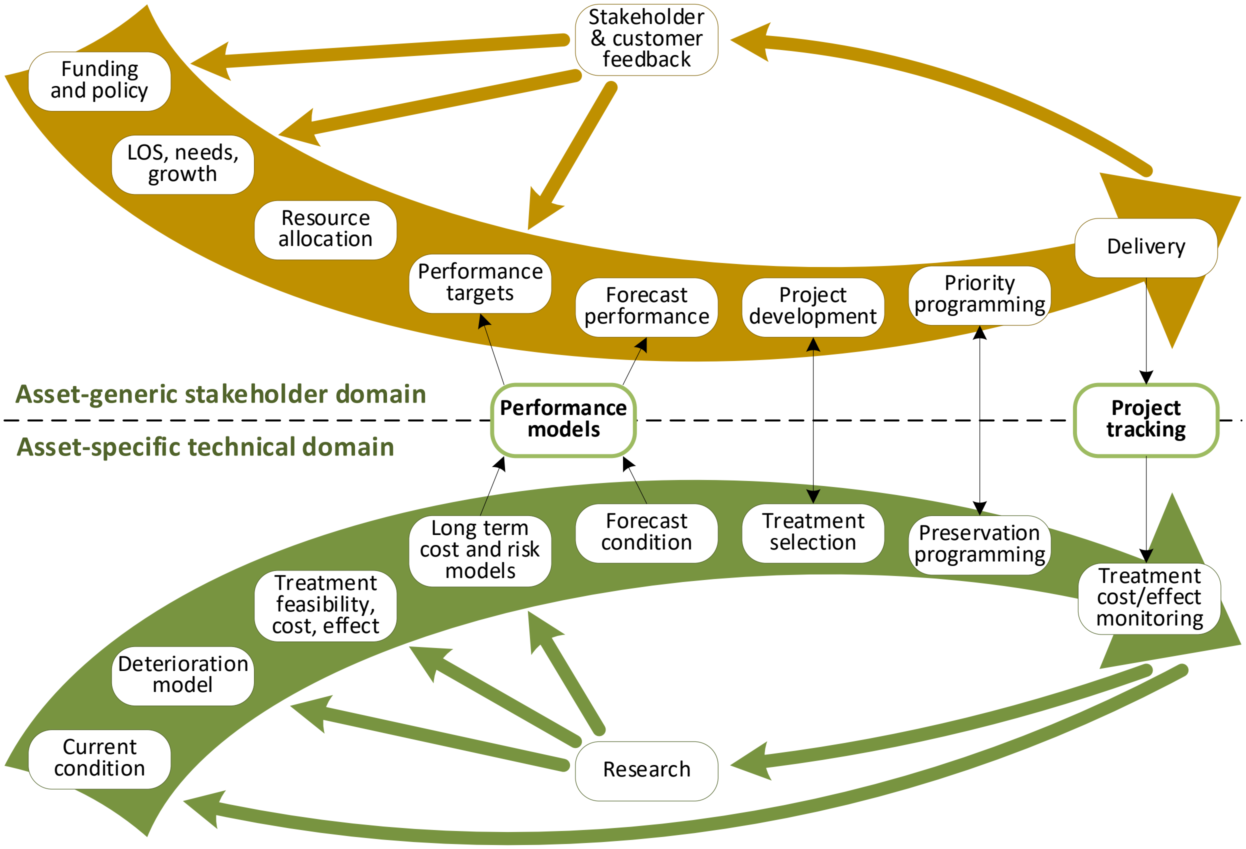
[16] Thompson, P. D., S. Sadasivam, and J. Mallela. *Identification of Effective Next-Generation Pavement Performance Measures and Asset Management Methodologies To Support MAP-21 Performance Management Requirements, Volume II: Methodologies To Enable Full Implementation of a Comprehensive Asset Management Plan*. Unpublished internal report for phase I of project. Washington, DC: Federal Highway Administration.

used for pavements are significantly different from those used for bridges, geotechnical assets, and other classes. TAM systems have developed to serve this entire cycle of needs.



Source: FHWA.

Figure 3. Illustration. System support of TAM business processes.

Because management systems employ the needs, methods, traditions, and terminology of each asset class, there is a set of unmet needs (figure 3) that cross the boundaries of asset classes because they serve the network as a whole. This perspective uses performance models that convert forecasts of asset class performance into general network performance and a process to track the implementation of all types of projects so that management has a uniform picture of work accomplishment and cost.

The types of decisions made in these business processes typically look ahead to objectives and outcomes 10 years in the future. This timeframe agrees with the timeframe often used in TAMPs, but some processes may pertain to timeframes that are longer or shorter than the TAMPs. The TAM planning methods incorporate important types of uncertainty that are found on that timescale regarding such matters as deterioration rates, costs, and funding. On this timeframe, programs of projects usually take the form of annual project lists or budget allocations and are updated each year in an annual budgeting cycle. Some agencies, however, use a biennial cycle. This report often refers to a 10-year program horizon and a 1-year decision interval because these increments are the most common. However, the methodology is equally applicable to other timeframes on the same order of magnitude.

Tradeoff Analysis

As a part of each of these business processes, agencies face decisions that relate current choices about work to be done (e.g., maintenance, preservation, rehabilitation, reconstruction, network expansion) to future expectations for network performance. Changes in the allocation of resources in the near-term can be expected to lead (in cause and effect fashion) to changes in performance later. If the agency allocates an increased share of funding to urban highways, for example, then urban network performance should be expected to improve, relative to rural performance. Similarly, a focus of resources on safety in preference to other goals should result in a greater improvement in safety relative to other goals.

To adopt a result-oriented approach to decisionmaking, agencies need modeling tools that estimate future performance based on near-term actions. These tools use quantitative data about current asset inventory and performance, scientific and statistical understanding of deterioration processes, cost structure, project delivery capabilities, and treatment effectiveness. The tools then convert this information to estimates of network performance at a future point in time.

Some of the needed tools already exist in the form of PMSs and BMSs, but the ability to examine this tradeoff in an asset-generic way is missing. This type of examination enables decisions that are not asset-specific (such as budgeting and programming) to be related to the stakeholder-relevant measures of network performance. Additionally, such an examination enables these decisions to maintain consistency with the technical analysis already being provided by management systems.

Differential Effects on Performance and Cost

A complication that arises in developing a cross-asset tradeoff analysis is that different asset classes and treatment types affect performance and cost in different ways. Pavement management decisions tend to be driven by surface condition, both because this aspect of performance can be reliably measured and because many aspects of condition have either a direct effect on road users or on further deterioration. Models of safety and mobility, particularly models of the risk of service disruption, are not as commonly found in PMSs because these effects of pavement performance are uncommon in developed countries. PMSs used in the less-developed world, such as the Highway Development and Management Model (HDM-4), use these models (Archondo-Callao 2008). Additionally, FHWA's HERS quantifies safety and mobility consequences of pavement investments (FHWA 2005).

On the other hand, bridge management decisions place more emphasis on safety and mobility, as bridge geometrics and load-carrying capacity have a direct effect on road users. Meanwhile, most material conditions (other than severely deteriorated) do not. Bridges are more vulnerable to extreme events that can disrupt transportation services by compromising safety and mobility. Yet condition is still a significant factor in bridge decisionmaking, since deterioration (if left unchecked) can eventually reduce load-carrying capacity. Bridge condition assessment is complex and labor-intensive, but it is valuable because timely knowledge of deterioration can lead to the most cost-effective responses.

Other asset classes are even more strongly oriented toward safety and mobility than bridges. Many traffic control devices are resistant to any type of condition assessment—they either work or do not work. They are replaced when they either stop working or reach the end of their recommended life, but preservation work is rarely done.

Additionally, different types of treatments have differential effects on performance and cost. For example, pavement resurfacing may be effective against deteriorated surface conditions, but it is not effective against a weak subgrade that causes rutting. The painting of a steel bridge is effective when only minor corrosion is present; however, it cannot remedy severe section loss. The concept of treatment feasibility is specific to each asset class and indicates whether the treatment can be applied and if it is an appropriate cure for the present conditions.

Types of treatments also differ in their cost structure, especially regarding indirect costs, such as work zone traffic control, mobilization, engineering, demolition, environmental protection, and land acquisition. Many types of preservation treatments have costs that are roughly proportional to deteriorated quantities. On the other hand, reconstruction and rehabilitation projects tend to have a cost structure that is less correlated to current conditions.[17] For these more extensive projects, relatively high costs and long durations resulting from traffic protection measures and detour installations increase the likelihood that multiple assets (even entire corridors) can cost-effectively be serviced in the same project.

Role of This Study

The goal of the present study was to demonstrate a cross-asset, multi-objective tradeoff analysis methodology that is grounded in management system data and models; conforms to the goals, objectives, and targets published in TAMPs; and responds to the needs of TAM business processes common in transportation agencies. Using an example tool and multiple pilot tests, one way of completing the linkage from asset-specific technical analysis to stakeholder-oriented network performance was demonstrated as a means to support result-oriented decisionmaking.

In this role, the present study differs from other recent efforts. For example, National Cooperative Highway Research Program (NCHRP) Report 806, *Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance,* provides a cross-asset, multi-objective methodology founded on decisionmakers' opinions and stated preference structure rather than on data and engineering models. The report provides space for a variety of difficult-to-quantify objectives, but such objectives may go well beyond the scope of most TAMPs (Maggiore et al. 2015). In a similar vein, NCHRP Report 511, *Guide for Customer-Driven Benchmarking of Maintenance Activities*, provides a methodology based on customer survey data (Hyman 2004). NCHRP Report 590, *Multi-Objective Optimization for Bridge Management Systems*, takes a different approach, addressing multiple objectives in a manner closely tied to management system data but limited to structural asset classes that use element-level State condition data (Patidar et al. 2007).

Data-centered models like those described in NCHRP Report 590 have considerably less flexibility than opinion-based models since they are limited by data collection processes and the availability of data and research into engineering and economic phenomena (Patidar et al. 2007). The research team believes this rigidity can be an advantage in asset management because the inertia of data collection and research processes ensures that decision support is stable over time and is not overly sensitive to near-term changes in leadership or stakeholder representation. This rigidity also enhances transparency, helping ensure the goals and objectives stated in the TAMP remain the goals and objectives that drive decisionmaking over a long period of time. This goal

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[17] For pavements, maintenance and rehabilitation actions are still functions of asset condition. However, reconstruction may not necessarily correlate with current condition.

alignment supports the development of accurate forecasting models and increases agencies' abilities to make long-term commitments to performance targets.

At the same time, data-centered models cannot address all the important considerations in project-level decisionmaking, due to limitations of data and research. The tools developed in this study are for decision support, not decisionmaking. They make data more useful and usable in asset-generic management decisionmaking but do not replace the need for good judgment and the accountability of management for the quality of decisions.

PERFORMANCE MEASURES FOR CROSS-ASSET TRADEOFF ANALYSIS

TAMPs characterize pavement and bridge performance at a given time for a given network in standardized ways that comply with Federal rules (Office of the Federal Register 2017). The definitions of these measures are complex and differ for each asset class but are backed by a long history of research, specifications, training programs, third-party equipment, information systems, and standard operating procedures. Thus, they are repeatable over time and across the country, making them useful as a means of tracking network performance and setting long-range goals.

One type of measure emphasized in TAMPs is the percentage of a network in Good condition and Poor condition, with precise definitions of Good and Poor (Office of the Federal Register 2017). Pavements and bridges both use these measures, but a bridge in Good condition is different than a pavement in Good condition. Likewise, a bridge in Poor condition is different than a pavement in Poor condition. It is better to have 40 percent of a pavement inventory in Good condition than 30 percent. Yet comparing 40 percent of a pavement inventory in Good condition to 40 percent of a bridge inventory in Good condition is not possible. Additionally, it is not possible to determine whether a rating of 40-percent Good is more or less efficient, from an economic perspective, than a rating of 30-percent Good. The latter would cost less to maintain in the short-term but might cost more in the long term if the desired LOS is to be maintained.

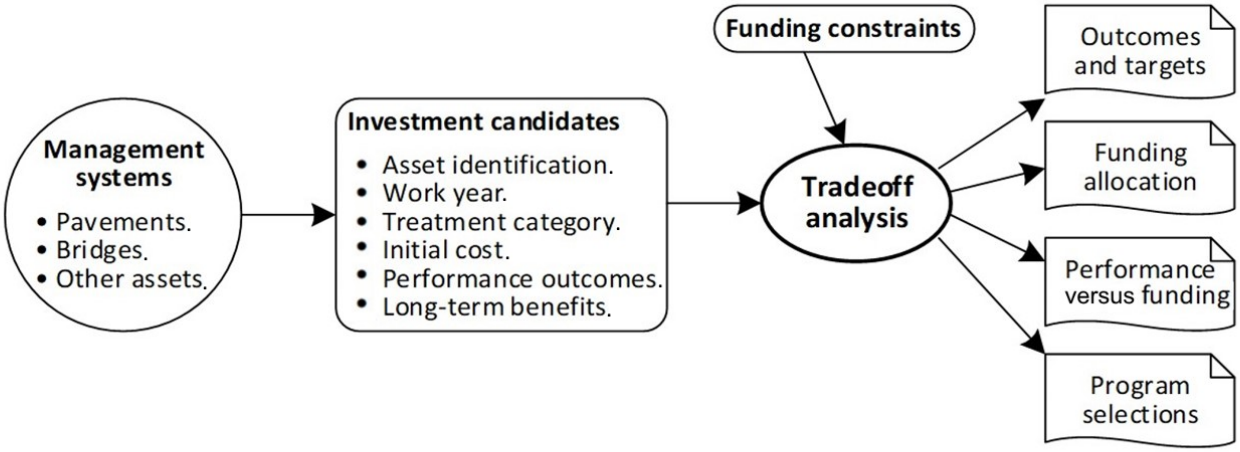
Chapter 2 investigated the potential for additional pavement performance measures that might support other purposes, such as setting priorities or programming future work. Some of these measures provide an economic context, in addition to a conditional context. Some measures are suitable for analyzing intertemporal tradeoffs because they consider the time value of money. When extending the concept to cross-asset tradeoff analysis, the challenge is to find at least one measure of network performance that has the same interpretation for pavements, bridges, and any other significant asset class and is suitable for cross-asset business processes that involve tradeoffs among asset classes, among objectives and over time.

In reviewing the capabilities of existing PMSs and BMSs used by State governments, the research team found no instances where these systems routinely produced a suitable cross-asset measure of performance for use in cross-asset resource allocation or priority setting. However, many of these systems did have suitable data and capabilities on which such a measure might be built. Most had some sort of model for programmatic cost estimation, and some could make intertemporal comparisons among project alternatives that consider the time value of money. Agencies desiring to use a cross-asset tradeoff analysis typically had categories of funding that could be readily moved among asset classes.

Definitions of asset performance characteristics (such as condition) vary widely from one asset class to another. However, economic characteristics are much more universal—provided that tradeoffs are not biased by differences in lifespans among various classes of assets and all the most relevant dimensions of performance (including safety, mobility, and sustainability) are considered.

One of the key findings of this study and a key theme of its conclusions is that the current capabilities of management systems do not implement data-based cross-asset tradeoff analysis, thereby reinforcing what are often called "silos" or disciplinary boundaries. However, some relatively modest enhancements to such systems could greatly enhance this support. These enhancements would use capabilities that already exist, in many cases—or capabilities that would exist if such systems were not exposed to access by outside systems and were fully compliant with Federal requirements (Office of the Federal Register 2017).

Capabilities of management systems can potentially be harnessed to support cross-asset tradeoff analysis. As illustrated in figure 4, management systems can potentially produce sets of investment candidates, characterized by attributes that can be expressed in a sufficiently generic way to make them comparable.[18] The tradeoff analysis can then use a prioritization scheme to provide decision support for common TAM business processes.



Source: FHWA.

Figure 4. Illustration. Harnessing management systems to support cross-asset tradeoff analysis.

Defining Investment Candidates

Before defining a set of performance measures, it is useful to first define the objects whose performance is to be measured. The decision context in the top part of figure 3 relates to the selection, scoping, timing, and delivery of units of work that claim an identifiable portion of agency funding and affect the performance of an identifiable portion of the transportation network. Moreover, most of these processes are network level, in that the collective effect of decisions is evaluated based on the performance of the entire network. These considerations imply two levels of analysis, as follows:

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[18] Based on Thompson, Sadasivam, and Mallela.. *Identification of Effective. . .Vol. II: Methodologies To Enable*.

- Investment candidates, which are projects or other units of agency work that cost a given amount of money and affect a given part of the network.[19] A single bridge or pavement section can have multiple alternative candidates that may be selected in different years or with different scopes of work, depending on funding availability. For the sake of simplicity, it is assumed in this study that only one candidate will be selected for any given bridge or pavement section within the 10-year program horizon. However, this assumption can be generalized to more complex multiyear or multiasset projects if sufficiently elaborate tools are developed.

- Networks, which are collections of all the assets whose overall performance is to be measured. In TAMPs, it is common to define one network as the NHS and another network as the non-NHS State highway systems (SHSs). Depending on the decisionmaker's scope of authority or interest, smaller or larger networks could be defined.

At these levels of analysis for the business processes of interest, two kinds of performance measures are needed, as follows:

- Outcome measures forecast the performance of the network at a future point in time. In keeping with the common practice in TAMPs, this study focuses on a 10-year time horizon for the reporting of predicted outcomes. PMSs and BMSs most commonly generate work programs and investment plans on this timescale.

- Prioritization measures compare the characteristics of different investment candidates to support the selection of a subset of candidates in each year in a way that optimizes network performance and cost. These measures thus provide a link between available investment candidates and network-level constraints and objectives.

Use of the term "optimize" in the preceding bullet does not necessarily imply any sort of formal mathematical optimization. It merely implies that a prioritization measure helps in programming investment candidates in a way that tends to increase overall network performance.

Outcome measures do not necessarily have to share an identical meaning across asset classes, though such measures are desirable when possible. On the other hand, prioritization measures need to be fully compatible across asset classes since they will compare, for example, a bridge investment with a pavement investment. The comparison should be fair even though these assets use significantly different technologies, have different cost structures and lifespans, and affect road users in different ways.

Estimating Performance

Decisionmaking that is data-driven and result-oriented is informed by a set of models that attempt to forecast the ways in which agency decisions will affect future performance. Figure 5 illustrates the main components that are generally found in these models (FHWA 2017).

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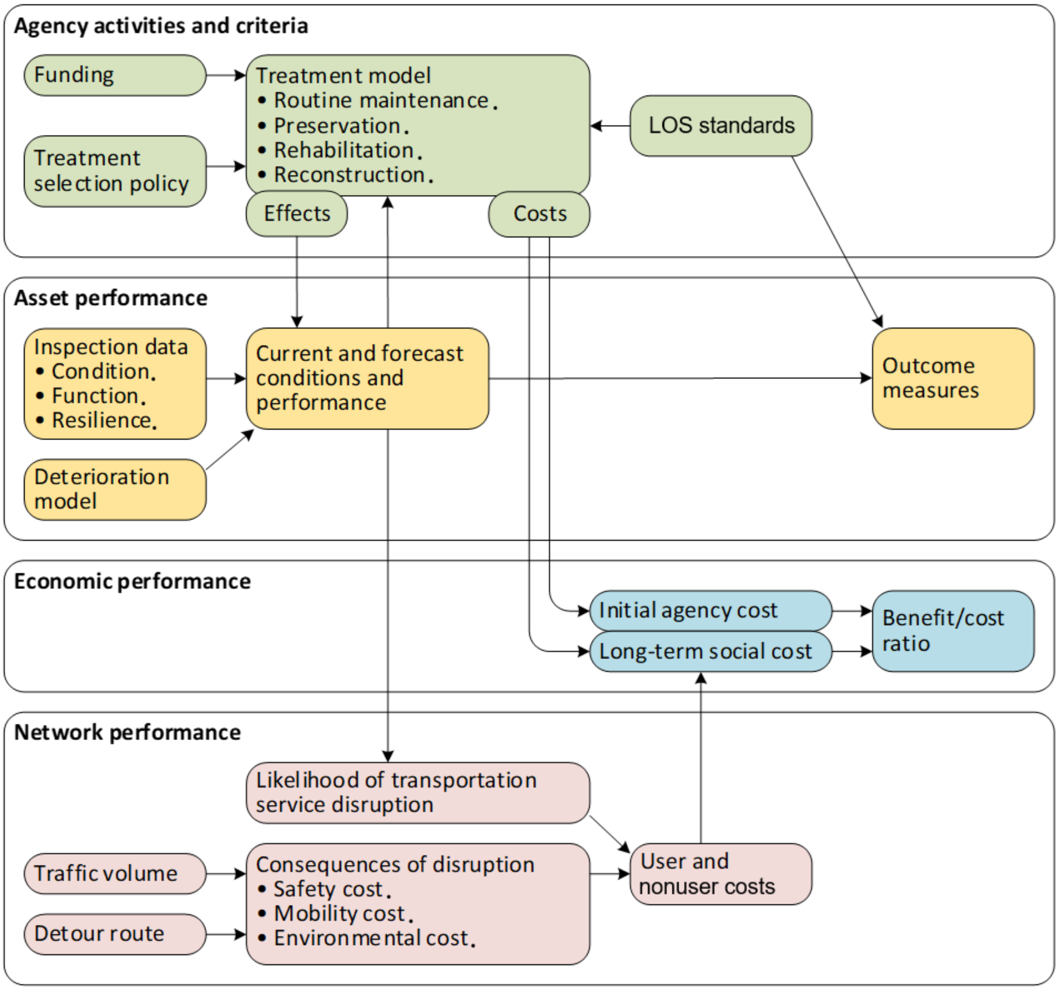
[19] In pavement management terminology, investment candidates are analogous to treatment strategies or investment strategies that include a sequence of potential treatment actions and associated costs over a chosen analysis period.

Traditional management systems typically focus on maintaining an inventory of assets with up-to-date data on physical condition, functionality, and resilience, which amounts to the ability to continue functioning at the desired LOS in the face of external hazards. The asset performance section in figure 5 illustrates that management systems often have deterioration models that forecast changes in condition, enabling the estimation of future outcomes of agency activities.

An agency can influence asset performance through its maintenance, preservation, rehabilitation, and reconstruction activities. These activities are driven by infrastructure funding and controlled by agency policies. The treatments that agencies apply to their assets have measurable effects on performance and costs that can be estimated and recorded. Standards for the LOS that are provided by each asset help identify assets that need corrective action and distinguish acceptable asset performance from unacceptable asset performance.

The first two portions of figure 5 are asset-specific in that the form of their data and analysis depends on characteristics unique to each asset class. Agency activities may be organized into projects for work that is in the delivery process. Work that is proposed and being considered for funding is organized into investment candidates, of which multiple alternatives may be under consideration.



Source: FHWA.

Figure 5. Illustration. Components of successful TAM models.

Certain management systems provide the capability to model external hazards or functional deficiencies that could cause parts of the network to fail to fully serve their intended functions. This situation commonly occurs with bridges and certain geotechnical assets, such as cut slopes. Deteriorated pavement or bridge deck conditions can cause traffic to slow or may force limitations on truck access. Impaired clearances and load-rating restrictions can also limit truck traffic. Earth movement, floods, and many other hazards can force the closure of network links. Any event that causes unnecessary detours or speed change cycles can increase pollutant emissions. As shown in the lower portion of figure 5, quantitative models of these phenomena typically adopt a probabilistic risk-based approach that forecasts user and nonuser costs based on asset and network characteristics affecting safety, mobility, and environmental sustainability.

The third portion of figure 5 shows that TAM models often have the capability to summarize agency, user, and nonuser costs into an economic quantity known as long-term social cost. This economic quantity is a convenient means of combining otherwise dissimilar economic quantities in a form that can be used for priority setting and resource allocation. If benefit-cost analysis (BCA) is a requirement (as it is in 23 CFR 515.17) and both benefits and costs are understood to be economic quantities, then a calculation of long-term social cost is the most direct way to measure benefit (CFR 2021c).

Outcome Measures

In a tradeoff analysis, outcome measures help decisionmakers assess the degree to which agency objectives may be accomplished by a given set of policies and resource allocations within the program horizon. Starting with a given program as a base, the allocation of resources may be adjusted to change the forecast outcomes in response to stakeholder concerns, policy goals, and equity considerations. Given a total fixed amount of funding, adjustments in resource allocation cause changes in relative performance outcomes. Some may improve; meanwhile, others decline.

Condition

Federal rules provide clear definitions for condition performance measures (Office of the Federal Register 2017). As such, these measures are used directly in the proposed tradeoff analysis. Each bridge or pavement section is classified as Good, Fair, or Poor, according to a combination of condition indicators. For pavements, the network performance measures are the percent of network lane-miles on sections in Good or Poor condition. For bridges, the network performance measures are the percent of network deck areas on bridges in Good or Poor condition.

Nearly all PMSs and BMSs in use in the United States can compute these measures from current inspection data. Some have developed capabilities to predict future values of these measures based on deterioration models, treatment effectiveness models, and fiscally constrained selections of work to be programmed. Unfortunately, standardized condition measures in this form do not yet exist for assets other than pavements and bridges.

Safety

Performance measures for other types of transportation goals do not yet exist in the same form as for condition. Some agencies use accident rates as a measure of safety, but these data are difficult to use, given that accident rates depend strongly on driver and vehicle characteristics and thus are not always reflective of infrastructure characteristics. An alternative approach is to define a set of asset properties that constitute a desired level of safety, which are used together to provide a standard LOS. For example, pavements might be characterized by skid resistance, width, and shoulder features. Bridges are characterized by roadway width, approach alignment, and deck surface condition. Assets that satisfy the LOS standards are deemed *Sufficient*. The network performance measure for safety is the percent of the network assets classified as *Sufficient* for safety.

Mobility

As with safety, it is possible to define LOS standards for mobility and to classify assets according to whether they satisfy the standards. This possibility is not often considered for pavements, but it is important for bridges, which can have standards for clearances and for load-carrying capacity. Trucks that are unable to use a bridge due to clearance and load restrictions are inconvenienced by having to detour. FHWA's (2005) HERS features a mobility model that is applicable to pavements and simulates speed reduction on pavements with high levels of roughness, reflecting inconvenience to drivers. The National Bridge Investment Analysis System (NBIAS), an investment analysis tool developed by FHWA to assess national bridge investment needs and evaluate the tradeoff between funding and performance, uses a similar model for bridge deck surface condition (FHWA 2021; Cambridge Systematics 2011).[20] The network performance measure for mobility is the percent of the network assets classified as *Sufficient* for mobility.

LOS standards can vary by functional class or other network characteristics. For example, a designated truck route might have higher standards for geometrics and load-carrying capacity than the rest of the network.

Environmental Sustainability

Researchers and tool developers have not yet addressed concerns about environmental sustainability at the same level as they have addressed other performance concerns at. However, the Federal HERS model does contain a set of features that reflect the public health impacts of air pollutant emissions. This model places emissions within the same framework as mobility, in that detours and speed change cycles increase the emission of pollutants. The Federal HERS model does not yet consider carbon dioxide emissions or climate change impacts (FHWA 2005).

Prioritization Measures

PMSs and BMSs often offer decision support for the programming of investment candidates using BCA. In this framework, projects receive higher priority as their benefits increase and lower priority as their costs increase. Usually, such systems are provided with a fixed-budget constraint and set up to maximize the best network performance possible under that fixed budget. In its simplest form, this prioritization is done by sorting investments by benefit-cost ratio (BCR). More complex models can consider multiple scoping alternatives or a continuously variable range of possibilities using various types of mathematical programming algorithms, such as analytic hierarchy process. (The article "Application of Analytic Hierarchy Process in Network Level Pavement Maintenance Decision-Making" discusses using this topic in more detail (Li et al. 2018)).

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[20] FHWA. 2019. *NBIAS* investment analysis tool (software). Version 5.3.

BCA is so ubiquitous in management systems that it is familiar to most agencies and is a logical organizing framework for the tradeoff analysis. The ability to generate programmatic cost estimates is well-established even though the indirect cost portion (especially work zone traffic control and mobilization) is still immature and requires further research. Appropriate accounting and budgeting conventions can ensure that cost estimates are compatible across asset classes so that they can compete for a shared budget.

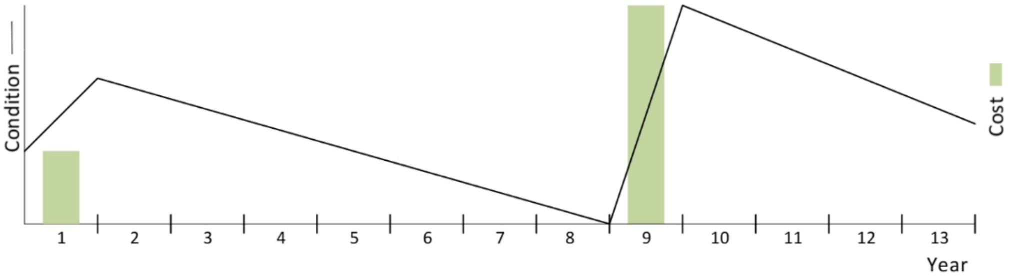
For this study, the challenge is defining a benefit measure for the numerator of the BCR. Such a measure should account for the most significant performance consequences of investments in such a way that it is appropriate for every asset class to be included. This measure should consider differences in scope and timing among alternative investments in a consistent way, even when the competing investments differ substantially in scale and service lifespan. As in most typical asset management practices, decisions will consider the existing network and exclude (or separate) network expansion or contraction. These decisions do, however, require continuity of service; thus, agencies may want to consider replacing existing assets at end-of-life and risk disrupting a network with extreme events.

Prioritization in a benefit-cost framework can be visualized as a sequence of comparisons between two alternatives, as follows:

- Do something: An investment candidate is selected for implementation this year for a given asset. Its cost is immediately set aside from the available budget, and the indicated work is assumed to be implemented. This action will affect the future stream of costs, a period where no additional work may be necessary may occur, and then the asset will resume normal deterioration and risk. This period is followed by additional costs to respond to deterioration and keep the transportation link in service.

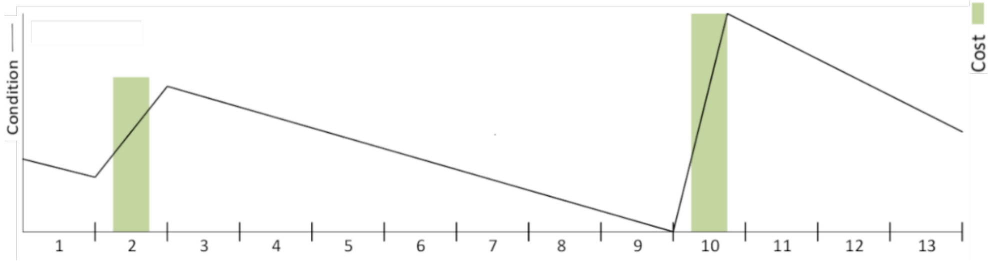
- Do nothing: No investment candidate is selected this year for a given asset. No immediate cost is incurred, and no work is done. The asset incurs an additional year of deterioration and risk. An appropriate work candidate, whose work may be more expensive due to additional deterioration and risk, may be selected next year if sufficient funds are available.

Figure 6 illustrates the difference between these two approaches using simple long-term activity profiles. In this example, the do-something alternative has a moderate preservation cost in the first year, improving the condition, and then a reconstruction cost in year 9, which places the asset in *New* condition. The do-nothing alternative takes no action in the first year, allowing further deterioration. A more expensive treatment is selected in the second year, which changes the timing of work that comes later. In this simplified example, the do-something alternative would likely have the lower NPV for long-term cost.



Source: FHWA.

A. Do-something alternative.



Source: FHWA.

B. Do-nothing alternative.

Figure 6. Graphs. Comparison of example asset's NPV for long-term cost in do-nothing and do-something scenarios.

It is straightforward to compare first-year costs (the denominator of the BCR) between these two alternatives because the second alternative has a first-year cost of zero. For the numerator, two approaches are commonly used, as follows:

- A utility function may be computed as a weighted sum of all the positive attributes that the do-something alternative can deliver and the do-nothing alternative cannot.
- A long-term social cost may be computed for each alternative. This cost includes the consideration of long-term agency and user costs either combined or independently, depending on agency preferences. If the do-nothing alternative has a higher long-term social cost than the do-something alternative, then the difference is the benefit of selecting the do-something strategy.

The calculation of user and nonuser costs is typically simplified by computing only the difference between the alternatives (i.e., the value of the avoided user and nonuser costs if the do-something strategy is selected).

Both of these approaches have complications. For the utility approach, there is no objective way to decide how much weight to give each positive attribute of an alternative. Various types of survey methods of preference structure elicitation can be performed, but the results will change as leadership and stakeholder representation change because they are inherently subjective.

User and nonuser costs, which include the economic value of travel time, vehicle operating costs, and accident-related costs, can be determined from research and are readily available in publications such as AASHTO's *User and Nonuser Benefit Analysis for Highways*, also known as its Red Book (AASHTO 2010). This analysis is not always simple, but because it is standardized and widely used, it is less subjective. In fact, social cost is a type of utility function that is based on economic research rather than on elicitation of opinion.

Intertemporal tradeoffs are fundamental because budget constraints imply that certain investments, with their costs and benefits, should be delayed. Both utility and cost have a time-dependent value. For each year a benefit is to be delayed, its value is reduced. If costs can be delayed, then each year of delay is a benefit. Discounting of costs is a familiar concept: If one wishes to buy a house, one will often take out a mortgage so that the benefits of homeownership can be enjoyed immediately rather than waiting to save up the large amount of money needed. In return for accelerating the benefit (ignoring any future change in resale value) and delaying the cost of ownership, an additional charge is incurred for mortgage interest. Discounting of utility is just as real but is much less familiar to most people.

Additionally, using a utility-based approach does not avoid the need to assign economic value to positive outcomes. For preservation investments in particular, the savings in lifecycle agency costs are a primary motivating factor. These savings mean that the utility function still must assign an equivalent utility to the savings in long-term agency cost that may be achieved through preservation. Each unit of utility has an implied dollar value even if it is not stated in dollars.

Given the relative strengths and weaknesses of the two approaches, the social cost approach was selected for the present study. With the utility approach, there would be a risk that consistent objective weights for positive transportation system attributes might be difficult to obtain in a way that did not have inherent bias among pavements, bridges, and other asset classes. Such bias would be difficult to discover and correct and would constitute additional moving parts in a model that the research team desired to keep as simple as possible.

LCCA is the term commonly used to describe the methodology of identifying long-term cash flows required to maintain service and compute a discounted NPV (FHWA 1998). However, for many TAM purposes, using the term “long-term cost analysis” is more accurate. The relevant cost stream extends beyond the lifespan of the asset in question, as it includes the cost of constructing and maintaining replacement assets necessary to maintain service on a transportation network link over the long term.

Intertemporal Tradeoffs

The proposed framework operates on sets of investment candidates that are generated separately for each program year by management systems. Within a program year, the management system considers a set of feasible treatments for each asset for implementation that year, assuming that nothing was done in the preceding years. The management system generates a long-term activity profile (i.e., a sequence of activities, user costs, and nonuser costs over a long period, including replacement of the current asset at the end of its economic life) for each treatment by following a set of policies and decision rules. The trade-off analysis tool selects the treatment with the lowest NPV of long-term social cost (sum of agency, user, and nonuser costs) (FHWA 2024b). The stream of cash flows for each treatment is discounted to the program year in which a treatment is being considered. If there are no treatments feasible in the subject program year that can reduce the long-term social costs, it is appropriate to select the do-nothing strategy.

In this framework, intertemporal tradeoffs are inherent in the long-term cost calculation and the selection of project scope for a given year. That is where discounting of future costs takes place. Therefore, when considering the do-nothing investment candidate in the cross-asset tradeoff analysis, the 1-year delay in work does not cause an additional year of discounting. Rather, it means using the investment candidate that was selected for the following program year, which typically will have a higher initial cost and higher routine maintenance costs (because of further deterioration) and may have an entirely different long-term activity profile if the nature of the selected work is different.

Ensuring Compatibility Among Asset Classes

Regardless of the approach chosen, the methods for calculating BCR fundamentally depend on the asset class. For example, the estimation of long-term agency cost depends on a deterioration model, whose form and parameters differ greatly between pavements and bridges. Cost structure also differs, including the criteria and costs for end-of-life replacement. The effect of investment candidates on safety and mobility also differs by asset class due to their differing relationships to traffic.

Therefore, the framework delegates many decisions to the individual management systems and is structured to avoid certain questions that could raise incompatibilities among asset classes. The following are examples:

- The system will assume that effective work on each asset is to be done eventually to achieve and maintain a desired LOS. Thus, it does not consider the possibility of removing a link from the network if it becomes unsafe or impassable. It therefore reduces the decision to a question of timing—act this year or next year. Without this assumption, the framework would become considerably more complicated; it would need to consider capacity and congestion on alternative routes, differences among asset classes in their unmaintained service life, and the effects on the public of intentionally declining LOS (such as paved roads becoming unacceptably rough).

- The system can make separate decisions for each asset class about the characteristics of replacement assets. However, reconstruction should always be considered for each asset if this action is necessary to keep the transportation link open. For consistency, it is best if reconstruction costs are estimated under an assumption that the number of lanes in a link is unchanged. This assumption makes system expansion a separate question with its own costs and benefits. PMSs and BMSs in their current form generally do not consider system expansion.

- The framework is calibrated to fit a set of broadly defined treatment categories (e.g., do nothing, preservation, rehabilitation, reconstruction) that can be understood in a similar way across all asset classes. Each management system can analyze treatments in as much detail as desired (e.g., the thickness of a bridge deck or a pavement overlay), but only the less-detailed categories are needed for cross-asset tradeoff analysis.

- The asset class management systems will determine what types of treatments are most appropriate to consider at any given time for a given asset and select the one in that year with the lowest long-term cost available. As defined here, the cross-asset tradeoff analysis considers timing alternatives but not scoping alternatives. This exclusion enables a simple benefit-cost ranking to suffice for prioritization and resource allocation. The framework can be extended to consider scoping alternatives as well, but then the tradeoff analysis algorithm would need to be more elaborate (e.g., incremental BCA, mathematical programming) (FHWA 2011).

- The work benefits and disbenefits should affect the benefit-cost calculation in a way that is meaningful for each asset class since the tradeoffs are encapsulated within a long-term cost calculation. If deteriorated conditions, risks, or functional deficiencies exist that affect road users, then a delay of work should cause an increase in social costs. Building a reconstructed facility to higher safety or mobility standards may cause a decrease in user and nonuser costs. A cross-asset benefit-cost comparison is not meaningful unless all relevant benefits and costs for each investment candidate are included.

Provided that each management system considers all these factors, the BCR used in prioritization is merely the ratio of the increase in benefit (or decrease in social cost) divided by the initial cost if the do-something alternative is selected rather than the do-nothing alternative. The means of calculating this measure do not have to be the same across management systems; however, standardizing certain conventions in long-term cost analysis will improve the compatibility and understandability of the analysis, as follows:

- Separate management systems will use the same discount rate in calculations of the time value of money. In a program-level analysis where positive and negative risks are spread among a great many individual decisions, it is typical to use a discount rate greater than the "risk-free" Federal treasury bond rate, but less than the rate typically used in project design studies. The research team suggested that inflation be removed from the discount rate and used instead to reduce the buying power of budget constraints, so that all asset classes are affected equally. The research team had observed real discount rates, in practice, to range from 1.8 to 2.5 percent in various agencies.

- Different asset classes can use different analysis periods in their long-term cost calculations. Each asset class should use whatever period is appropriate for treatment selection, which may depend, in part, on the typical lifespans of different asset classes.

- Social cost representation conventions are oriented so that the factors adding to the benefit of a do-something alternative have a positive sign and those relating to the disbenefit of the do-something alternative have a negative sign. Neutral considerations should not affect the sign. Therefore, BCRs can be expected to be non-negative. If a do-something alternative has a negative BCR, it is more attractive to delay the work, regardless of funding constraint. Thus, the do-nothing strategy should be selected.

- Separate management systems can make the cross-asset analysis simpler by suppressing treatments that are inappropriate to a given set of conditions that are not cost-effective (i.e., that do not reduce total long-term social cost) or whose total long-term social cost would decrease if the work were delayed. If all available treatments are suppressed by these considerations, then it is appropriate to select the do-nothing strategy in the cross-asset analysis.

- Inherent work should increase the total long-term social cost with these conventions in most cases, therefore yielding a positive number in the numerator of the BCR. (Inherent work means work delayed 1-year that is inherent in the do-nothing alternative.) An exception would occur if the do-something alternative has no effect on any agency, user, or nonuser costs. For example, if replacement is the only available treatment but asset characteristics and conditions are not yet affecting replacement cost, routine maintenance cost, or any road user concerns, then there is no consequence of delaying the work and the numerator would, therefore, be zero. Another exception may occur if the change in condition caused by a 1-year delay renders a treatment infeasible, and the next available treatment is not yet cost-effective.

Some of these conventions may differ from the conventions that may have been chosen when a given PMS or BMS was designed. As a result, there could be a need for modifications to these systems in some cases to ensure compatibility among systems. Depending on the system architecture, the modifications might be limited to a module that computes and exports data for cross-asset analysis. In other words, the BCR used for cross-asset analysis does not necessarily have to be the same as the BCR used for other purposes within a PMS or BMS.

Availability of Cross-Asset Measures

Given that outcome measures and BCRs depend on asset class, these performance measures are ideally computed by asset-specific management systems. Indeed, PMSs and BMSs that have a planning capability consistent with Federal rules often compute these measures (or similar ones) internally in support of their program development functions. Unfortunately, these systems do not typically output the results of these calculations (for complete sets of work candidates) in a form that can be used in cross-asset tradeoff analysis.

Often, the reason for this functionality gap is a lack of software that can make use of such a dataset and thus a lack of demand for this feature. Of course, the lack of data sources is one reason that cross-asset tradeoff analysis tools are not more widely available. In working with the three State agencies in the pilot testing phase of the study, the research team was able to develop the following two-part response to this circular problem:

- Develop a specification for a dataset called the investment candidate file, which provides the minimum set of data required for the proposed tradeoff analysis. This process is described in chapter 4. Having such a specification may make it easier for developers of management systems to provide a function to easily export the necessary data.

- Develop or adapt example applications as additional spreadsheets that perform example sets of calculations of these performance measures using PMS and BMS data (described in appendix E). Given that many TAM systems are proprietary products that do not publish their calculation methods, open-source implementations of example models that can be published and serve as proofs of concept for future developers are needed.

The commercially available systems could undoubtedly offer more options and functionality than the open-source examples. But the examples did allow the pilot studies to go forward despite a lack of directly applicable data. If developers eventually offer features to export the needed work candidate data, the example adaptations may eventually become unnecessary.

TRADEOFF ANALYSIS ALGORITHM

Using the outcome and benefit-cost prioritization measure discussed in this chapter, the TA-MAPO tool can be used to forecast the results of any given decision scenario with a relatively simple algorithm. A series of decision scenarios can be developed that represent alternative fiscal scenarios, alternative allocations of resources, and/or alternative policies. A set of targets, expressed in the form of the outcome measures discussed here *(%Good* condition, *%Poor* condition, *%Sufficient* for safety, *%Sufficient* for mobility), can be used to assess whether a given scenario is likely to achieve its intended objectives. If the targets are not all satisfied, adjustments can be made in the decision scenario to attempt to find a more satisfactory solution. If no solution satisfies all the targets, then it may be necessary to adjust the targets (FHWA 2024b).

Figure 7 is a flow chart of this algorithm.[21] Investment candidates are prioritized by BCR in each year, and the top-ranked candidates are selected, subject to funding constraints. Candidates that cannot be selected are delayed, which may cause additional social costs. Performance outcomes for the network are the combined result of asset deterioration and the effects of all the investments that can be performed within the funding constraint.

New decision scenarios can be prepared by making changes in the policies that generate the investment candidates. An even quicker method is to allow weighting factors to be applied to the components of social cost representing agency costs, safety-related user costs, and mobility-related user costs. This allowance takes advantage of the fact that social cost is used in the same manner as a utility function. Initially, all types of costs may be given equal weight, but the agency may decide to increase the weight assigned to an objective (or to a portion of the network) to improve the performance of that portion of the program. The idea of shifting money to a part of the program that needs better performance is intuitive to program managers.

This algorithm is a common feature of PMSs and BMSs, as well as a feature of many internal spreadsheet programs that agencies have built to support capital-budgeting exercises. The main difference here is that the performance measures used in the algorithm are constructed to be as asset generic as possible to enable tradeoffs involving multiple classes of assets (especially pavements and bridges).

To assist in the potential implementation of these measures, a spreadsheet implementation was developed by the research team and pilot tested in three agencies. This activity is discussed in the next chapter.

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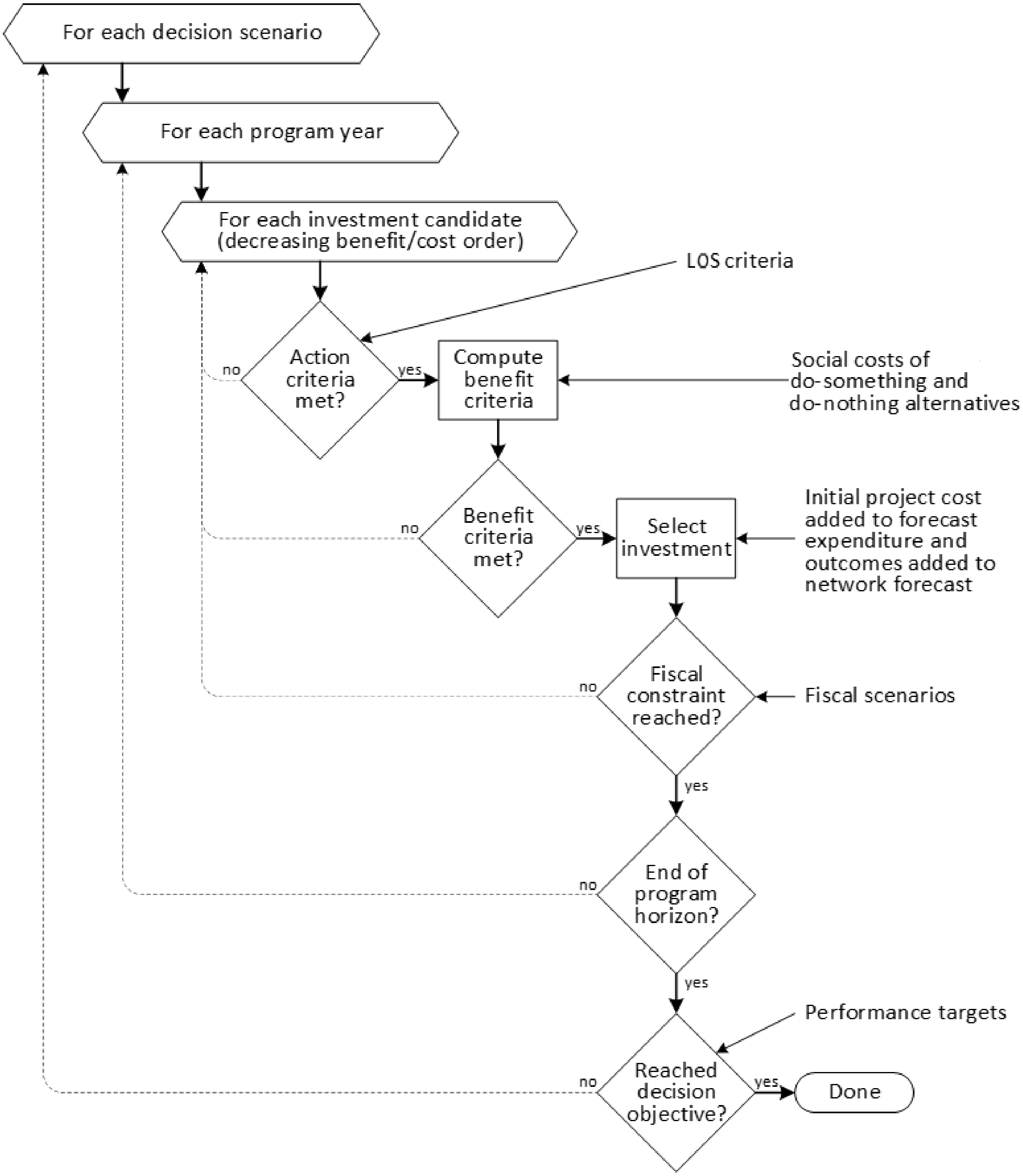
[21] Thompson, Sadasivam, and Mallela. *Identification of Effective. . .Vol. II: Methodologies To Enable.*



Source: FHWA.

Figure 7. Flowchart. Tradeoff analysis algorithm.

CHAPTER 4. STATE VALIDATION PLANNING

INTRODUCTION

Current pavement performance metrics are based on conditions—or, more specifically, on the presence or absence of specific types of distress or defects in the pavement. These condition-based measures provide an assessment of performance at the time of measurement, but they do not directly inform decisionmakers on the best approach for achieving performance goals in the future. Such measures are commonly referred to as "lagging." They are useful for measuring compliance with goals and objectives, or for setting targets, but are not well-suited for determining the best method of meeting future goals, objectives, or targets.

The NGPPMs described in chapter 2 were selected for validation largely because they hold promise for use as leading indicators. That is, they provide insight into the likelihood that future performance objectives will be achieved. The two categories of performance measures provide these insights in different ways, as follows:

- Lifecycle measures support the evaluation of different lifecycle treatment strategies for addressing pavement needs over the long term. These measures consider current conditions, ideally in terms of both pavement surface distress and structural capacity, and proposed series of future treatments. The treatments are defined in terms of cost, initial condition improvement, and future deterioration to evaluate LCCs. Using this information, the lifecycle measures support comparison of the proposed treatment strategies to determine which strategy provides the lowest LCCs.

- Financial measures support the evaluation of different treatment strategies, also; however, they do so by comparing the financial implications of each. These measures provide an assessment of the future costs or liabilities resulting from each strategy.

Currently, State DOTs and other highway agencies rely heavily on the distress measure forecast to compare different LCP and investment approaches. While these forecasts provide a reasonable assessment of future conditions, they do not indicate the efficiency with which the proposed treatment strategies are achieving these conditions, and they do not provide agencies with a simple means of distinguishing between strategies that provide similar results. The NGPPMs present an opportunity to provide highway agencies with additional means of understanding the long-term implications of their pavement management decisions. If successful, these measures could support the development of more efficient and more effective pavement management strategies, allowing agencies to achieve better pavement conditions, reduce costs, or both.

The performance measures discussed in chapter 2 are strictly forward-looking measures, intended to support planning decisions by forecasting the likely future results of policies and resource allocations under consideration. They are selected to be as independent as possible from asset-specific considerations, so they can be used in cross-asset tradeoff analysis. The BCR developed in chapter 3 is based on the same type of LCCA described for the performance measures in chapter 2 but is defined so as to be unbiased by differences in service life, technology, and road user impacts that exist among different classes of assets.

VALIDATION OBJECTIVES

As discussed in chapter 1, the NGPPM and proposed TAMM validation objectives were as follows:

- Validate through pilot implementation the promising NGPPMs described in chapter 2.
- Validate through pilot implementation the proposed TAMM to enable full implementation of a comprehensive asset management plan (including tradeoff analysis from a common ground among disparate assets that are traditionally assessed individually and managed by a State DOT).

Before starting the validation efforts, the research team sought to develop a consensus on what the term “validation” means. For this research effort, validation was defined in terms of the following:

- Measures can be calculated with available data.
- Measures can be applied for practical use by the validating agency.
- Measures can be applied to the validating agency’s decisionmaking processes.
- Measures can be used to inform the proposed TAMM.
- Methodology can be implemented with available data.
- Methodology can be used to improve outcomes.

The research team developed an approach to validate the NGPPMs and proposed TAMM at the State level.

SELECTION OF AGENCIES FOR STATE VALIDATION STUDIES

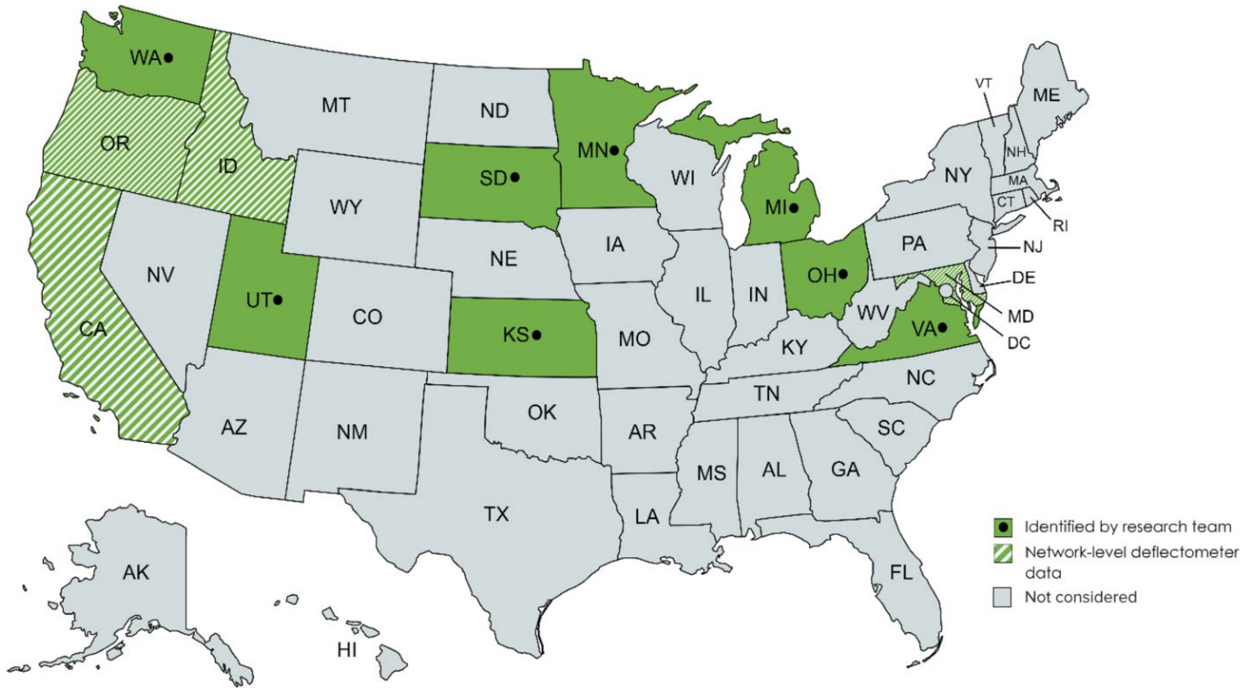
Based on feedback from FHWA, the research team conducted the State DOT validation studies in phases. This phased approach resulted in three rounds of selections of pilot agencies—an initial round held in February 2019, a second round held in May 2020, and a final round held in April 2021.

Initial Selection Round

The research team used the following criteria for the initial selection process:

- Availability to participate in the validation efforts.
- Desire to implement research results after completion of the pilot.
- Quality of available data, tools, and resources to support the validation efforts.

Based on this selection criteria and the research team’s professional experiences and relations with the agencies, the team identified the 12 State DOTs (figure 8) that seemed to have the most potential to successfully validate the NGPPMs and proposed TAMM. Eight of the 12 States—Kansas, Michigan, Minnesota, Ohio, South Dakota, Utah, Virginia, and Washington—were targeted based on contact the research team had with agency representatives after phase I ended and phase II began. The other four States—California, Idaho, Maryland, and Oregon—were targeted because they possessed network-level falling weight deflectometer (FWD) data that could be used to support the RSI measure.



Original map © MapChart. Modified by FHWA (see Acknowledgements section).

Figure 8. Illustration. Candidate validation States (MapChart 2024).

State Agency Survey and Phone Interviews

After identifying the 12 candidate State DOTs, the research team conducted an initial ranking to prioritize the agencies according to who was most able to support the validation efforts. As a result of the initial ranking process, the top four agencies were identified as Idaho, Kansas, Michigan, and Minnesota. Before interviewing each of the top four agencies, the research team distributed a web survey to them. The goal of this survey was to assess the data, tools, and resources each agency would have available to support the validation efforts. Table 3 summarizes the main questions in the web survey.

Table 3. DOT web survey questions.

Pavement Data Questions	Bridge Data Questions
What measures do you collect, and how long have you been collecting them?	What is your BMS? If BrM, what modules do you have configured to your needs?
To what extent do you have FWD/RWD/TSD data?	What measures do you use for treatment selection?
How confident are you in your deterioration models?	Have you used your BMS to generate LCCs for specific bridges?
Do you use your PMS to generate LCCs for specific pavement segments?	How confident are you that your decision tree selects the lowest LCC option?
How confident are you that your decision tree selects the lowest LCC option?	How confident are you in your service life predictions for specific treatments applied to specific conditions?

RWD = rolling weight deflectometer; TSD = traffic speed deflectometer.

After each of the top four State agency candidates submitted their survey responses, the research team conducted a phone interview with each agency. The interview questions were distributed before the interview, so the agency could prepare responses. The goal of the interview was to assess the agency's availability, willingness, and capability to participate and implement the validation and its corresponding performance measures and TAMM. The phone interview agenda is provided in table 4.

Table 4. DOT phone interview questions.

Assessment Area	Questions
Assess State DOT's willingness and availability to participate in validation efforts	How would you assess your agency's ability to support the following project activities: • Provide data extracts for each asset? • Provide multiple management system runs? • Provide input for calculation of NGGPMs? • Evaluate and comment on preliminary and final results? • Support configuration of tradeoff tool? • Evaluate tradeoff results and provide comments? • Support finalization of tradeoff tool?
Evaluate State DOT's desire to implement results of research	Are you satisfied with the current means of prioritizing pavement investments? If you could improve something about your capital program development, what would it be? Are you looking to implement asset management for more than pavements and bridges? Does your agency currently have a cross-asset or cross-program tradeoff tool? Do you have staff who could support the upkeep and use of a tradeoff tool? Are staff who manage the PMS and BMS open to changing their approach? Does your agency makeup allow for alternative methods to allocate funds and select projects, or are you locked into a process?
Evaluate State DOT's financial data	Do you allocate funding based on performance criteria? If so, what criteria are used? Do you select projects based on performance criteria? If so, what criteria are used? Are you able to link project costs to accomplishments and asset condition? If so, please describe the datasets and business processes used. Are you able to link maintenance costs to accomplishments and asset conditions? If so, please describe the datasets and business processes used. Describe how you track project costs through delivery phases. Describe how you tie capital and maintenance accomplishments back to asset inventory, work history, or condition status. How would you describe the integration of your financial and asset management data?

State Agency Evaluation and Selection

The research team compiled the survey and interview results for each agency into an evaluation matrix composed of the following assessment factors:

- Evaluation criteria:
    - Sufficient resources for the effort.
    - Management support for the effort.
    - Analysis capabilities for the methodology.
    - PMS capabilities.
    - BMS capabilities.
    - Other capabilities for asset management systems.
- Data availability and quality for RSI analysis:
    - Deterioration models for condition metrics (e.g., IRI, rutting, and cracking for pavements) (CFR 2017b).
    - Treatment strategies.
    - Yearly costs for the analysis period.
    - Good/Fair/Poor condition assets for each year (Office of the Federal Register 2017).
    - Segment number/percent with treatment needs in the following categories: do nothing, maintenance, preservation, rehabilitation, reconstruction (or other categories, as defined by agency).
- Data availability and quality to support the AUCR measure:
    - Deterioration models for condition.
    - Treatment strategies.
    - Yearly costs for segments in the network over the analysis period.
    - LCCs for chosen analysis period.
    - Data on programmed annual costs and actual annual costs at the network level for each asset (AUCR measure only).
    - AUCR forecasting ability.
- Data availability and quality to support the CAR measure:
    - Condition performance models.

  - Treatment strategies.
  - Yearly costs over the analysis period for the network segments.
  - Treatment histories.
  - Optimized lifecycle strategy with policies for the analysis period.
  - CAR forecasting ability.
- Data availability and quality to support the ASI measure:
  - Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).
  - Budget needs determined using the management system.
  - Yearly allocations to address the needs determined through the agency's financial planning process, which accounts for expected revenues and is adjusted for inflation.
  - ASI forecasting ability.
- Data availability and quality to support the ASR measure:
  - Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).
  - Current replacement values.
  - Asset value depreciation.
  - ASR forecasting ability.
- Data availability and quality to support the ACR measure:
  - Condition performance models, treatment strategies, and treatment costs.
  - Current replacement values.
  - Asset value depreciation.
  - ACR forecasting ability.
- Data availability and quality to support the SLR measure:
  - Condition performance models, treatment strategies, and treatment costs.
  - Management system funding required to address the total needs identified.
  - Financial planning funding committed to address the total needs identified.
  - SLR forecasting ability.

For each of the factors, qualitative ratings (Very Good, Good, Adequate, Poor, Very Poor) were assigned for each of the four surveyed and interviewed agencies. The completed evaluation matrices are provided in appendix A.

Following a careful review and comparison of the four evaluation matrices, Idaho was identified as the most suitable candidate State. The primary reasons for ITD's selection included the following:

- Good quality data available (including partial network-level FWD data).
- PMS and BMS capabilities.
- Dedicated agency staff time and resources given willingly to support the validation effort.
- Interest in and likelihood of implementing the validation results.

Subsequent Selection Rounds

During analysis of the Idaho validation, the research team reviewed the results of the original State selection to identify potential candidates for a second validation. Taking into consideration the information gathered in round 1, the research team gave preference to agencies with the following:

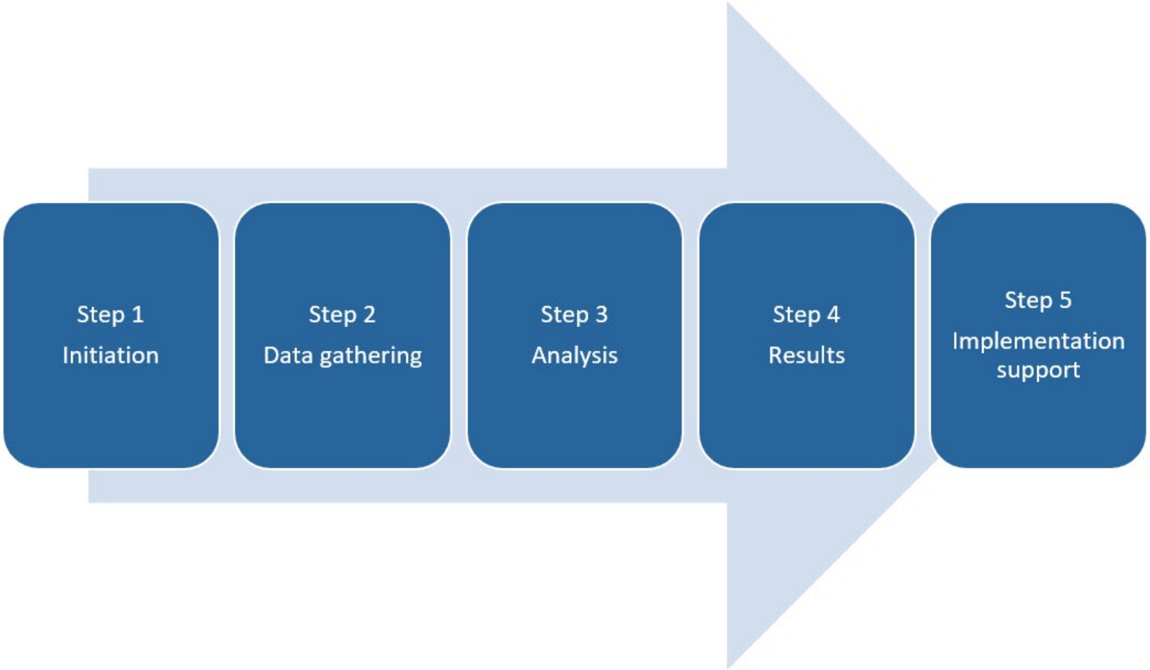
- Use pavement decision trees and deterioration curves that consider treatment history and condition at the time of treatment.
- Possess a PMS from a different vendor than used by Idaho.
- Maintain the ability to solicit support and input from the PMS vendor.

Based on the review and these modified criteria, the research team scheduled an interview with SDDOT in June 2020. During the interview, the team determined that SDOT met all the additional criteria and was interested in both supporting the validation effort and implementing any promising results. SDDOT's pavement management staff, research staff, and bridge management staff all expressed interest in implementing the cross-asset tradeoff analysis.

In early 2021, the research team and FHWA agreed to extend the project to include a third validation effort. The extension was granted due to delays incurred as a result of the COVID-19 pandemic. At that time, the team sought to identify a State agency that met all the listed criteria and had a more diverse inventory of pavement types. This goal led the research team to reach out to TxDOT in April 2021. FHWA and the research team interviewed TxDOT on April 26, 2021. During the interview, TxDOT staff expressed interest in supporting the validation effort and offered to provide analysis for pavements and bridges from two districts. Each district managed more assets than either of the first two validation agencies. TxDOT staff also noted that they had a standing support contract with their PMS that could be used to support the needed analysis.

STATE VALIDATION APPROACH

The State validation approach consisted of five sequential steps, as illustrated in figure 9. Although the same format was followed for each agency, some modifications were made to meet each agency's needs and accommodate restrictions put in place in response to the COVID-19 pandemic. Each validation study was closely monitored and documented to capture the experiences and lessons learned in investigations and to develop key implementation guidance, such as the changes needed in existing datasets and asset management systems.



Source: FHWA.

Figure 9. Illustration. State validation process.

Step 1. Initiation

The research team envisioned this step to include a two-step kick-off meeting with both virtual and in-person formats to support development of a detailed validation workplan. The team held the initial kick-off meeting as a teleconference that included the research team, FHWA technical lead, and State technical lead. The teleconference provided an opportunity to introduce the key team members, discuss roles and responsibilities, provide an overview of the project and schedule, and prepare for the larger in-person workshop. The teleconference was followed by an in-person workshop that enabled the research team and FHWA to engage with key stakeholders and leaders at the State DOT.

For ITD, this two-step kick-off began with an initial conference call in July 2019 and a 2-day, in-person meeting at the ITD offices in August 2019. During the in-person meeting, the research team met with pavement and bridge management staff and finance and programming staff. The scope of the meeting was similar to that of the initial kick-off call, but the in-person meeting provided an opportunity for much deeper discussions into topics such as available data and potential implementation opportunities.

This process was changed for SDDOT and TxDOT, in part due to restrictions put in place for the COVID-19 pandemic and in part due to the change in the selection process. For both agencies, the interview conducted to support selection served a similar purpose as the initial kick-off call. This interview allowed the State agency personnel who would be most involved in the project an opportunity to understand the project objectives, their roles, and the required level of effort. Due to travel and meeting restrictions for COVID-19, the in-person kick-off meetings for SDDOT and TxDOT were changed to web conferences. These web conferences covered the same topics as the in-person meeting with ITD but were conducted virtually and over several meetings scheduled for shorter periods of time.

Following the kick-off meeting, the research team developed a detailed workplan to guide the validation process at each agency. The workplan for each State validation followed a similar format, as detailed in table 5. The timeframes for each validation task varied by agency.

Table 5. State validation workplan.

Validation Tasks	Task Activities
Validation kick-off (2 mo)	Conduct 2-h kick-off call: • Introduce project team and objectives. • Provide project overview and background information. • Discuss project team roles and responsibilities. • Establish project schedule. • Discuss potential risks to successful validation. • Confirm communication protocols. • Discuss next steps. • Discuss data, tools, and information required from pavement, bridge, and finance groups for a successful validation process. Establish initial information request. Conduct initial validation discussion: • Provide project overview to the pilot State DOT and executive staff. • Discuss activities and schedule. Conduct separate meetings with pavement, bridge, and finance groups. Request initial pavement data from PMS.
Work plan development (2 mo)	Develop final work plan that does the following: • Details and defines roles and responsibilities. • Maps data to performance measures. • Explains strategy for addressing data gaps and risks. • Summarizes schedule for delivery.
Data gathering (5 mo)	• Discuss approaches for calculating and modeling RSI with FHWA panel; discuss any issues pilot State DOTS may encounter. • Request initial bridge dataset. • Review initial pavement data and identify challenges: • Ensure PMS data output file corresponds to selected lifecycle strategy. • Obtain SDDOT PMS data output file with all feasible lifecycle strategies the PMS generates. • Discuss inner workings of each State DOT's PMS, focusing on how the system models, calculates, and uses individual distress metrics to calculate benefits and select treatments. • Determine format and level of detail needed for financial data. • Request initial financial dataset. • Provide initial financial dataset. • Establish budget constraints for analysis. • Draft data map. • Document remaining unresolved issues and draft steps to overcome these issues. • Finalize data mapping between pavement dataset and performance measure calculation. • Determine lifecycle strategies to be used in validation (SDDOT only). • Request final pavement, bridge, and financial datasets. • Conduct long-term analysis to meet performance targets using agency management systems. • Conduct PMS and BMS analysis to provide output of viable treatment strategies. • Conduct PMS and BMS analysis of multiple viable budget scenarios.

Validation Tasks	Task Activities
Analysis: tool development (4 mo)	• Establish scope of any needed algorithms or tools, including data sources. • Develop draft pavement tools and algorithms to calculate needed parameters (asset value depreciation, CRV, DRV, NPV) for each asset in each year of the analysis period. • Develop draft bridge analysis tool to calculate needed measures for TAMM tool input. • Test pavement tools and algorithms with initial pavement and financial data. • Test bridge analysis tool with initial bridge and financial data • Finalize pavement tools and algorithms. Finalize bridge analysis tool.
Analysis: validation of performance measures (2.5 mo)	Calculate the following parameters for each year in the analysis period for each of the strategies considered in the previous step: • Fraction of asset network requiring the following actions: maintenance, preservation, rehabilitation, reconstruction, and associated costs. (Other agency-specific actions may also be considered.) • Network value depreciation. • Network CRV. • Network DRV. Compute ASI, ASR, ACR, and SLR performance measures at the project level (when applicable) and network-level. Conduct the RSI analysis (SDDOT only). Conduct analysis to validate the proposed TAMM.
Results (2 mo)	• Document preliminary performance measure results. • Document financial performance measures for ITD and TxDOT. • Conduct RSI analysis (SDDOT only). • Present analysis results and discuss plans to implement research results into agency TAM processes. • Identify final adjustments to data, models, or analysis approach (if needed) based on agency feedback. • Conduct web meetings to review pavement analysis and TAMM analysis. • Present analysis results and discuss initial plans for implementing research results into agency's TAM processes. • Identify any final adjustments to the data, models, or analysis approach that are needed based on agency feedback. • Assess validation to determine if additional analyses are required for completion. • Adjust data, parameters, tools, and algorithms (if necessary) as needed to finalize results. • Rerun performance measure and methodology analysis as needed. • Document analysis results and any adjustments to data, tools, or algorithms.

DRV = depreciated replacement value.

Step 2. Data Gathering

Following the kick-off meeting, the research team made several data requests to each pilot State to facilitate the analysis process. The requested data were primarily composed of outputs from each agency's PMS and BMS and supplemented with additional supporting information. Key considerations in the data-gathering effort included the following:

- Appropriate and adequate data for calculating performance measures and supporting cross-asset tradeoff analysis.
- Suitable complexity of the scenario, availability of staff time, and anticipated volume of data to be provided.
- Adequate representation of a meaningful portion of the agency's highway system.
- Reasonable mix of conditions and treatment needs.

Data Needed for Validating the Next-Generation Pavement Performance Measures

The raw pavement data output files provided by the pilot States in response to the data requests included the following information:

- Pavement segment description.
- Treatment/activity for each year in the analysis period.
- Treatment/activity category (e.g., maintenance, preservation, rehabilitation, and reconstruction).
- Treatment/activity cost.
- Resulting improvement in pavement condition following treatment application.

The data elements required to compute the NGPPMs were identified from the tendered data output files. Common data elements needed from each DOT for the performance measure validation effort are as follows (agency-specific details that supplement this list are provided in appendix B through appendix D):

- Segment identification (ID).
- Functional class.
- Traffic.
- Pavement type.
- Performance measures.
- Optimized lifecycle treatment strategy (including costs).
- Suboptimal lifecycle treatment strategies (including costs).
- Budget needs.
- Allocated budget to address budget needs.
- Annual and cumulative asset value depreciation.
- Current asset replacement value.

Notably, the team did not use all these data elements to calculate each of the measures, as some measures required more data elements than others. In addition, some processing and manipulation of the raw data was required to generate the required data elements. Details of these actions are provided in chapter 5 through chapter 7.

Data Needed To Validate Proposed Transportation Asset Management Methodology

To support the validation of the proposed TAMM, the project team developed a TA-MAPO spreadsheet tool. This tool, which is described and illustrated in detail in appendix I, demonstrates basic cross-asset tradeoff analysis by selecting from a set of candidate investments to meet budget constraints. The candidate investments come from management systems for pavements, bridges, and other asset classes. They represent a set of optimized work candidates available for programming in each budget period during the TAMP time horizon (usually 10 years). The investment units are characterized by their cost and their 10-year performance outcomes, which are expressed in an asset-generic way to the extent possible (FHWA 2024b).

Table 6 lists and defines the data needed to support the TA-MAPO tool in terms of the asset identification, current performance, and ending condition sections of the investment candidate file.

Table 6. Input data columns in the TA-MAPO tool investment candidate file (FHWA 2024b).

Column	Definition
Asset Class	Names the type of asset represented by each row of the table. Typically, a word such as "Pavement" or "Bridge." The terms used should agree exactly with those used on the target and allocation worksheets.
Asset ID	Unique identifier for each row; usually corresponds to a record in the management system database where the row originated (e.g., Bridge ID or Pavement Section ID).
NHS Asset	Yes, if the asset is a part of the NHS; otherwise, no.
Interstate Asset	Yes, if the asset is on the interstate highway system; otherwise, no.
SHS Asset	Yes, if the asset is a part of the SHS; otherwise, no.
District Asset	Name or number representing a district or other useful subdivision of the network: The terms used should agree with those used on the target and allocation worksheets.
Current Size	Quantity used in computing network outcome measures. For pavements, lane-miles; for bridges, deck square feet.
Current Replacement Value	Replacement value of the asset (in thousands of dollars).
Current *%Good*	*%Good* as defined in Federal rules. For an individual asset, this number is usually 100 or 0.
Current *%Poor*	*%Poor* as defined in Federal rules. For an individual asset, this number is usually 100 or 0.
Current Safety *%Sufficient*	Safety *%Sufficient*, as defined in chapter 3. This number is usually 100 or 0.
Current Mobility *%Sufficient*	Mobility *%Sufficient*, as defined in chapter 3. This number is usually 100 or 0.
Do Nothing *%Good*	Forecast *%Good* after the last period (year or budget cycle), computed by the management system using its deterioration model. If no work is done in any period, may be expressed as a probability.
Do Nothing *%Poor*	Forecast *%Poor* after the last period (year or budget cycle), computed by the management system using its deterioration model. If no work is done in any period, may be expressed as a probability.

Table 7 lists and defines the data that describe the investment candidates in terms of a given evaluation period (e.g., year or budget cycle). In this table, period 1 is shown, as indicated by "Period 1" at the beginning of each data element name. Additional periods are added as needed in subsequent columns, using the appropriate period identifiers.

Table 7. Input data columns repeated for each period in the TA-MAPO tool investment candidate file (FHWA 2024b).

Column	Definition
Period 1 Treatment Category	Treatment category: "DN" for do nothing, "preserve" for preservation, "rehab" for rehabilitation, or "recon" for reconstruction.
Period 1 Cost	Initial cost (in thousands of dollars)
Period 1 Forecasted Condition (10-year Outcome) *%Good*	Condition outcome *%Good*
Period 1 Forecasted Condition (10-year Outcome) *%Poor*	Condition outcome *%Poor*
Period 1 Forecasted Safety (10-year Outcome) *%Sufficient*	Safety outcome *%Sufficient*
Period 1 Forecasted Mobility (10-year Outcome) *%Sufficient*	Mobility outcome *%Sufficient*
Period 1 Long-Term Agency Savings Benefit	From management system long-term cost analysis, savings in long-term agency costs if the treatment is done during the current year instead of waiting until the next year (or period) to act (in thousands of dollars).
Period 1 User Savings Benefit	From management system long-term cost analysis, savings in long-term user costs if the treatment is done during the current year instead of waiting until the next year (or period) to act (in thousands of dollars).

Step 3. Analysis

The validation analysis was conducted in two stages. The initial analysis focused on calculating the NGPPMs and determining their value to the agency. A second analysis was then performed to evaluate the agency's ability to populate and run the TA-MAPO tool using data from the agency's PMS and BMS. None of the three agencies were able to provide the data needed to support tradeoff analysis for assets other than pavements and bridges.

Validation of Next-Generation Pavement Performance Measures

Validation of the NGPPMs involved four separate analyses. Before starting analysis, the research team mapped data from each agency's PMS output files to the measure calculation spreadsheet. This mapping provided a framework for linking specific PMS data fields to the data elements needed to calculate the measures. The data mapping details for each agency are described in appendices B through D. The following is a summary of the four analyses:

- Analysis 1: Conduct a series of long-term analyses (preferably longer than 30 years) to determine the resources and treatment strategies needed to meet agency-established performance targets using each agency's PMS.
- Analysis 2: Use the PMS outputs and other relevant State agency information to calculate the following parameters for each year in the analysis period for each individual segment in the network using a simple spreadsheet-based tool:
  - Asset value depreciation (researchers may need to establish a depreciation calculation model based on discussions with the State agency).
  - NPV (calculated using an appropriate discount rate specified by the State agency).
  - EUAC.
- Analysis 3: Calculate the following parameters for each year in the analysis period for each of the treatment strategies considered in step 1 at the network level:
  - Asset network fraction requiring following actions (other actions specific to the State agency may also be considered): maintenance, preservation, rehabilitation, reconstruction, and associated costs.
  - Network asset value depreciation.
- Analysis 4: Compute the various performance measures at the project level (when applicable) and network level:
  - AUCR, CAR, and RSI at the network and project levels.
  - ASI, ASR, ACR, and SLR at the network level.

Validation of Proposed Transportation Asset Management Methodology

The validation of the proposed TAMM was conducted using the TA-MAPO tool (FHWA 2024b). As noted previously, appendix I describes and illustrates the use of the tool in detail. The validation process for each pilot agency included the following analyses:

- Analysis 1: Conduct a long-term PMS analysis for a pavement segment and a long-term BMS analysis for a bridge segment (preferably longer than 30 years) to generate multiple lifecycle strategies that meet agency-established performance targets. The data output will include multiple strategies for each segment where treatment is delayed 1 year at a time over a 10-year period.

- Analysis 2: Use the data outputs and other relevant State agency information to calculate (using a simple spreadsheet-based tool) parameters for each year in the 10-year period, for each segment in the network, and for each of the lifecycle strategies considered in step 1. Details of these actions are provided in chapters 5 through 7. The following are the parameters:

    - LCC calculations for each strategy over the chosen analysis period.

    - Long-term agency savings (calculation illustrated in appendix E).

    - Performance outcomes in terms of percent %*Good* and %*Poor* (calculation illustrated in appendix E).

    - Treatment category and total cost of the treatments triggered in the 10-year period.

    - Current asset replacement value.

- Analysis 3: Combine all the data into an investment candidate file, which forms the input to the TA-MAPO tool once the parameters are calculated for each pavement and bridge segment. This process is detailed in appendix I.

- Analysis 4: Input the investment candidate file into the TA-MAPO tool and perform a cross-asset tradeoff analysis. The following results are obtained from this analysis:

    - Compare 10-year performance forecast to the agency-specific performance targets.

    - Compare changes in asset condition with changes in funding allocations for pavements and bridges.

    - Address performance target feasibility, funding allocations, and funding alternatives.

Step 4. Results

The validation results, which were based on the analyses, were presented to each agency through a series of meetings. Technical results from the NGPPM analysis were presented to the agency technical leads in two separate meetings—one focused on the lifecycle measures and the other focused on the financial measures.

The research team presented and evaluated the initial NGPPM analysis results and then analyzed the proposed TAMM and presented the results in a separate meeting. In parallel, the research team revised and/or updated the pilot agencies' performance measure analyses based on input or additional information from the agencies. The team then presented final analysis results for both the NGPPM and proposed TAMM validations first to the agency technical leads and then to agency leadership. This final meeting provided an opportunity to gain leadership buy-in for implementation of specific measures or for use of the TAMM, where applicable. Additional details of these efforts are provided in chapters 5 through 7 and appendices F through H.

Step 5. Implementation

The research team offered implementation support to each pilot agency. After presenting the results, the research team worked cooperatively with agency technical leads to identify aspects of the analysis the agency felt would benefit their pavement management or asset management procedures moving forward. Using this information, the research team developed draft implementation plans in the form of spreadsheets, which the agencies can use to manage and track implementation efforts after the research team's support ended. Table 8 describes the spreadsheet fields and explains ITD's implementation plan.

Table 8. Implementation plan spreadsheet content.

Plan Element	Description	Example
Action	A brief description of the item or process to be implemented.	Set up calculation spreadsheet.
Step	A listing of the individual steps to be taken to accomplish the action.	Present recommended measures for implementation to executive staff.
Description	A brief description of each step.	Present the measures, discuss them, and confirm approval to move forward with implementation.
Assigned to	The party or parties responsible for conducting each step.	Research team.
Key stakeholders	The responsible (R), accountable (A) consulted (C), and informed (I) parties for the action.	R: Research team. A: ITD project team. C: Pavement management support contractor. I: Executive management, finance, pavement, and bridge team leads.
Delivery mechanism	Means of procuring or providing each step.	Webinar meeting.
Start	The year and quarter for work to begin.	Quarter 2, 2021.
Finish	The year and quarter for work to end.	Quarter 3, 2021.
Duration (months)	The difference between start and finish.	1 mo.
Notes	Additional information on each step.	Completed July 16, 2021.
Output(s)	The final product provided by each step.	Meeting notes confirming the implementation plan.

CHAPTER 5. IDAHO VALIDATION STUDY

VALIDATION PROCESS

ITD was the first State DOT selected to validate the NGPPMs and the proposed TAMM. After ITD's selection, the research team held a brief kick-off meeting to introduce team members, review the project, discuss the goals and expectations of the study, and identify any foreseeable challenges. Following this meeting, a preliminary work plan and project schedule were developed to establish a structured process and timeline for the validation efforts. As the validation study progressed, the approach and the work plan were customized to better suit ITD's pavement and asset management practices and data. Key changes to the plan were as follows:

- ITD's standard PMS analysis module was unable to generate multiple pavement lifecycle treatment strategies for each segment included in the pavement network, so implementing the RSI, AUCR, and CAR analyses using standard PMS outputs was impossible. In the absence of an RSI analysis, the project team was unable to identify ITD's most optimum pavement lifecycle treatment strategy for managing ITD's pavement network, which is a key input in calculating the other two lifecycle measures. Hence, AUCR and CAR were also not validated, and the results obtained from ITD's standard PMS analysis configuration were only used to validate the financial performance measures.

- The project's team was able to develop an ad hoc approach to simulate the RSI analysis using ITD's decision trees and performance models, but the approach required exceedingly long computation times to generate all feasible lifecycle treatment strategies for a 40-year analysis period. As a result, the approach was deemed impractical for implementation purposes and was not pursued further.

- ITD's PMS is able to generate alternative lifecycle strategies by determining the impact of delaying the recommended treatment by 1 year at a time over the chosen analysis period for each segment in the pavement network. This analysis module was configured and run by a third party serving as an independent consultant to ITD during the validation study. While this analysis also required long computation times, the process was mostly automated and could be run using the PMS. The analysis was conducted for a 20-year analysis period, and the results were used as the inputs for the TA-MAPO tool used for the TAMM validation process.

Next-Generation Pavement Performance Measures

ITD was interested in whether the NGPPMs could help it narrate an account of its pavement management process that could not have been communicated using existing pavement condition-based performance measures (cracking, rutting, roughness, overall condition, etc.). To accomplish this objective, the research team gathered and analyzed ITD's pavement management data, computed four financial performance measures (ASI, ASR, ACR, and SLR), and presented recommendations to ITD on how the measures could potentially be used to support existing business processes. The following is a brief description of the four steps involved in the validation process:

1. Determine data needed for analysis and review relevant supporting documentation: The research team worked with ITD to compile a list of the data needed to compute the performance measures included in the validation effort. Additionally, key ITD documents (e.g., 2019 TAMP, 2015 PMS configuration) were obtained and reviewed to help identify the parameters involved in calculating performance measures.

2. Review PMS analysis capabilities: The research team reviewed these capabilities thoroughly while working in close coordination with ITD's pavement team. The research team then identified a list of analyses that needed to be conducted with the PMS to enable NGPPM calculation.

3. Conduct PMS analyses: ITD's pavement team conducted PMS analysis runs that served as input to the calculation of the NGPPMs.

4. Calculate NGPPMs: The research team developed a simple calculation tool and used it to compute the NGPPMs based on the PMS analysis results from step 3.

Proposed Transportation Asset Management Methodology

In a series of workshops conducted in late 2019, ITD officials were introduced to the proposed TAMM. The research team asked ITD to provide, with consultant assistance, spreadsheet files containing pavement segments and bridges with identification data and 10 years of work candidates using a process similar to the NGPPM process described in the section directly before this one. The research team then input the pavement and bridge data into the TA-MAPO tool to demonstrate using benefit-cost prioritization criterion for the analysis of tradeoffs among costs and conditions across asset classes and subnetworks.

The ITD PMS was not capable of providing outputs in the needed format, so the research team needed to develop a separate spreadsheet model to accumulate PMS data and calculate the performance measures from multiple PMS analytical runs.

For bridges, ITD was implementing the AASHTOWare BrM. BrM does not have the capability to output a full set of work candidates in the needed format, although its database does contain all the necessary data to do so (AASHTO 2023). Fortunately, an open-source spreadsheet program, StruPlan, was nearing completion and had the ability to perform a similar network-level analysis and generate appropriate work candidates. Therefore, ITD was asked to provide a dataset compatible with StruPlan. The StruPlan user manual has a detailed description of the data format, which is further described later in this chapter (Thompson 2021).

Work candidates generated in this way from pavement and bridge data were combined into the assets worksheet of the TA-MAPO tool, forming an investment candidate file with the necessary prioritization measures and performance outcomes. The computations within TA-MAPO were then used to produce sample reports addressing performance target feasibility, funding allocation, and funding alternatives, which are all common examples of cross-asset tradeoff analysis (FHWA 2024b).

DATA AND INFORMATION GATHERING

This section presents details on the data- and information-gathering efforts for the performance measure validation process.

Data for Next-Generation Pavement Performance Measures Validation

Initial Data Request

Compiling a comprehensive pavement dataset to support NGPPM calculation was a key part of the validation effort. The research team held several web meetings with the FHWA panel and the ITD staff to pinpoint the specific information needed for the validation process (appendix B). As a result of these meetings, the research team requested and obtained four types of datasets and documentation from ITD.

Financial Data

ITD provided information on their current pavement budget level over a 40-year analysis period.

PMS Analysis Output Files

ITD provided sample PMS analysis output files for the research team to review as part of the initial data request. The following is a summary of the key data fields that ITD provided in their PMS output files:

- The pavement segment descriptions, including PMS section identifier, pavement type, direction, location, functional class, and number of lane-miles.
- The 40-year treatment selections, including treatment types, costs of treatments, and backlogs of unfunded treatment needs.
- The pavement conditions, using ITD's performance indicators. ITD follows a composite index approach computed by combining individual distress indices based on pavement type. These index values range from 0 to 100, with 0 indicating the worst condition and 100 indicating the best condition. The indices serve as decision points in ITD's PMS decision tree and help determine appropriate treatment types for pavements. The performance indicators include an OCI and various subindices used to calculate the OCI for flexible and rigid pavements, as follows:
    - Flexible pavements: The flexible pavement OCI is a function of the structural distress index (SDI) and the nonstructural distress index (NDI). The SDI is a composite index used to represent the overall structural condition of the pavement based on extent and severity of fatigue cracking, edge cracking, and patch deterioration. The NDI is a

composite index used to represent the overall functional condition of the pavement based on extent and severity of transverse cracking, block cracking, and raveling.

  - Rigid pavements: The rigid pavement OCI is a function of the slab index and the joint index. The slab index is a composite index used to represent the overall structural condition of the rigid pavement slab based on extent and severity of slab cracking and map cracking. The joint index is a composite index used to represent the overall condition of joints in rigid pavement based on extent and severity of joint seal damage, joint spalling, and faulting.

PMS Configuration Document

This document details how ITD's PMS was configured and implemented (Kercher Engineering 2015). The following items were used to configure the algorithms for calculating the NGPPMs:

- ITD's treatment categories and descriptions: The research team used the FHWA TAMP pavement work types—initial construction, maintenance, preservation, rehabilitation, and reconstruction, as per 23 CFR 515.13 (b)(2)(i)—for the validation effort (CFR 2021d). The ITD treatment categories were mapped to the FHWA work types. appendix B details this effort.

- Pavement condition index improvement rules: The pavement condition indicator is improved by a specific amount when a treatment is recommended during the PMS analysis. In addition to the condition improvement generated by treatment type, ITD's PMS includes supplemental improvement rules based on a host of other parameters, including the following:

  - Flexible pavements: Performance model type, type of last treatment (maintenance or other), years since last maintenance activity, friction number (FN), pavement age, pavement smoothness (IRI), and rutting.

  - Rigid pavements: Performance model type, FN, pavement age, map cracking extent, pavement smoothness (IRI), and studded tire wear.

- Exclusion years: ITD's PMS considers exclusion years for each treatment to force the PMS to wait a specific number of years before an equal or higher-level treatment can be applied. The treatment exclusion years based on pavement type are listed in table 9.

- Decision trees: ITD's decision trees use several parameters for identifying appropriate pavement treatments. These parameters include SDI, NDI, and rutting for flexible pavements; slab index, joint index, faulting, and studded tire wear for rigid pavements; and IRI, FN, and age since last treatment for both flexible and rigid pavements.

Table 9. Treatment exclusion years used in ITD's PMS (Kercher Engineering 2015).

Treatment Category	Treatment Exclusion Years	
	Flexible Pavements	Rigid Pavements
Preservation	7	10
Resurfacing	10	—
Restoration	12	12
Rehabilitation	15	15
Reconstruction	20	30

—Not applicable.

Structural Data

The research team selected ITD as the first pilot State partly because it had pavement structural condition data available (on a portion of the pavement network) that had been collected using a TSDD. However, the available structural condition data could not be linked to their corresponding PMS segments; thus, these data were not used in the validation effort.

Additional Data Request

The research team identified a few data issues while reviewing ITD's sample PMS data. These issues included inconsistencies in PMS treatment selections, treatment unit costs, and pavement condition deterioration trends. The research team worked closely with ITD pavement management staff to address the issues. Subsequently, they held a series of web meetings with ITD staff and finalized the parameters and budget levels to be used in the validation effort as follows:

- Analysis period: 40 years.
- Real discount rate: 2 percent.
- Lifecycle strategies: The research team and ITD identified three strategies for validating the NGPPMs: current, worst first, and ignore rigid pavement network. ITD opted to further investigate only the impacts of the current pavement management strategy, since it would yield more practical information to supplement their decisionmaking process. The current strategy refers to the default treatment optimization approach used by ITD's PMS, where treatment candidates were identified based on current and projected conditions that provided the maximum benefit (indicated as the area under the performance curve) at a given budget level.
- Budget levels: ITD ran the analyses using the current strategy followed by the PMS at seven different annual budget levels, ranging from $70 million to $270 million. However, based on ITD's preferences, only two of the seven budget levels were investigated further as part of the analysis—$85 million and $130 million.

Finally, ITD provided a PMS output file covering a 40-year analysis period for each PMS run requested.

Data for Transportation Asset Management Methodology Validation

Pavement Data

The advanced analysis module in ITD's PMS can perform a multistrategy analysis. This ability is conducive to generating inputs for the TA-MAPO tool. The analysis generated multiple strategies where the recommended treatments were delayed 1 year at a time over the chosen analysis period for a given segment. Through this type of analysis, ITD was able to identify the optimum time to apply a treatment on a segment and also consider a treatment's impact on other assets.

The PMS analysis also included the results of a do-nothing strategy and a maintenance-only strategy, which were also used as inputs to the TA-MAPO tool. Although the TA-MAPO tool conducted the analysis over a 10-year period, the PMS analysis was conducted for a 40-year analysis period to evaluate the long-term changes in LCC of delaying treatments.

To generate inputs for the TA-MAPO tool, ITD provided the data output files from the multistrategy analysis run over the entire pavement network covering a 40-year analysis period.

Bridge Data

The AASHTOWare BrM program performs a similar calculation internally for its own tradeoff analysis. However, it does not have the capability to create a file of work candidates that have the proposed tradeoff analysis performance measures (AASHTO 2023). It was determined that modifying the BrM was infeasible in terms of producing the necessary data within the time and resource constraints of the study. However, the open-source spreadsheet known as StruPlan became available in time to serve this purpose (Thompson 2021).

As discussed in more detail in appendix E, StruPlan performs a set of LCC calculations of the agency, user, and nonuser benefits of bridge work candidates and forecasts performance outcomes based on a set of analysis parameters and funding scenarios. It was determined that the StruPlan capabilities satisfied the timeframe and functionality requirements ITD was hoping to eventually achieve from the BrM and could be configured to incorporate the planning metrics (e.g., deterioration rates, unit costs, fiscal assumptions) that ITD had developed for the BrM up to that point (Thompson 2021; AASHTO 2023).

When the Idaho validation was initiated, ITD performed some initial analysis runs using the BrM. The agency was reasonably satisfied with the cost estimates the BrM produced but was not satisfied with the decision rules or selected work candidates (AASHTO 2023). The agency had been planning further development in these areas, but these plans were delayed by the COVID-19 pandemic. Therefore, the pilot study made use of the ITD unit cost data but used StruPlan's default decision rules and adapted the deterioration models in FHWA's NBIAS system for the cold, dry climate zone typical of Idaho (Thompson 2021; Cambridge Systematics 2011).[22]

ITD provided bridge and element data, with corresponding metadata, in April of 2020. The dataset included all NHS bridges and all State-owned bridges (including some that are not

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[22] FHWA. 1999–2024. *NBIAS* investment analysis tool (software).

included in the NBI) for a total of 1,903 structures. The data used in StruPlan included the following (Thompson 2021):

- Data about each bridge (identifier, district, facility carried, maintenance responsibility, owner, year built and reconstructed, design load, restriction status, type of service on and under, design type and material, length, width, deck area, vertical clearance, load rating, NHS designation, and appraisal ratings).
- Data about roadway carried by the bridge (bypass length, traffic and truck volume, functional class, number of lanes, and roadway width).
- Data from most recent inspection (inspection date, component condition ratings, and element condition records).

These data were provided in text files exported from ITD's BMS. A detailed description of the input data and options available can be found in the StruPlan user manual (Thompson 2021). In general, all the data items provided could also be found in annual submittals to FHWA's NBI and complied with FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA 2023,1995).

VALIDATION ANALYSES AND RESULTS

This section presents results of the Idaho NGPPM and proposed TAMM validation efforts. As noted previously, validations of the three lifecycle performance measures—RSI, EUAC, and AUCR—could not be performed due to limitations of the existing configuration of the agency's PMS.

Financial Performance Measures

The NGPPM validation efforts were focused on the following four financial measures:

- ASI: The ratio of the planned investment to the budget needed to maintain assets at a desired condition (Proctor, Varma, and Varnedoe 2012). The key parameter used in calculating the ASI measure is "pavement need," which is the budget needed to maintain the network at a desired SOGR.
- ASR: The ratio of the investments to the depreciation with having zero investment for a chosen fiscal period (Ram et al. 2023). The annual depreciation with zero investment was calculated by aggregating the annual depreciation calculated (discussed in the next section) and the pavement investment need. The pavement value depreciation used in the ASR calculation is based on the SDI for flexible pavements and the OCI for rigid pavements.
- ACR: The ratio of the depreciated replacement cost to the current replacement cost (Ram et al. 2023). ITD's PMS analysis runs do not consider new construction projects or inflation on treatment unit costs. Like the ASR, depreciation is a key parameter in calculating ACR.

- SLR: The ratio of the unfunded PMS treatments to the replacement cost of the pavement network (Ram et al. 2023). The unfunded treatments need/backlog is a direct output from the ITD's PMS analysis runs.

The research team initially planned to conduct validations of the three lifecycle measures (RSI, AUCR, and CAR) (Elkins et al. 2013).[23] However, successful calculation of these measures required the PMS to be capable of generating and evaluating all feasible lifecycle strategies for each pavement segment in the network. Although the research team tried to run this approach outside of the PMS, the process proved to be highly intensive computationally—and impractical from an implementation standpoint.

ITD's PMS includes an advanced analysis module that can evaluate the impact of delaying treatment during the analysis period. Using this module, ITD was able to run a multistrategy analysis run for a 20-year analysis period, which generated multiple strategies for each pavement segment. Because this run did not generate all feasible treatment strategies, a true RSI approach could not be implemented. However, the generated output was found to be suitable for the TA-MAPO tool used for the proposed TAMM validation, which considered a shorter period (10 years) for the tradeoff analysis. This topic is discussed later in this chapter.

Data Preprocessing for Financial Measures Validation

A major part of the financial measure calculation process was the identification of the necessary data elements from the PMS data output files (appendix B). Once the key data elements were identified, the research team then analyzed several parameters used in computing financial measures.

Pavement Condition Trends

The research team analyzed temporal pavement condition trends by plotting annual network-level weighted-average conditions over the 40-year analysis period. Figure 10 shows the SDI and OCI condition trends for three annual budget levels—$85 million, $130 million, and $200 million. The $85 million and $130 million budget levels resulted in constantly declining conditions over the analysis period. For the $200 million budget, the SDI decreased over the first 25 years but then underwent an appreciable improvement over the last 15 years. The OCI decreased over the first 7 years and then generally plateaued over the remainder of the analysis period. As discussed in the pavement need subsection, the $200 million budget run was used to establish this need.

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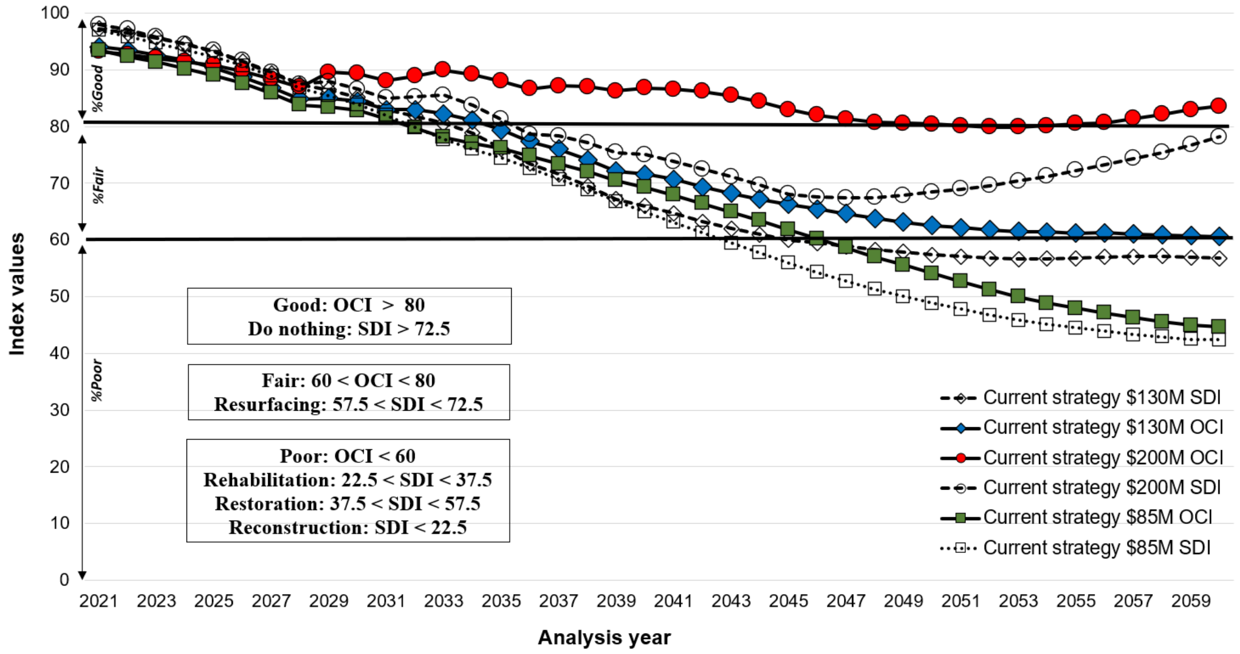
[23] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.



Source: FHWA.
Good: OCI > 80. Do nothing: SDI > 72.5.
Fair: 60 < OCI < 80. Resurfacing : 57.5 < SDI < 72.5.
Poor: OCI < 60. Rehabilitation: 22.5 < SDI < 37.5. Restoration: 37.5 < SDI < 57.5. Reconstruction: SDI < 22.5.
M = million.

Figure 10. Graph. Pavement condition trends for alternative annual budgets.

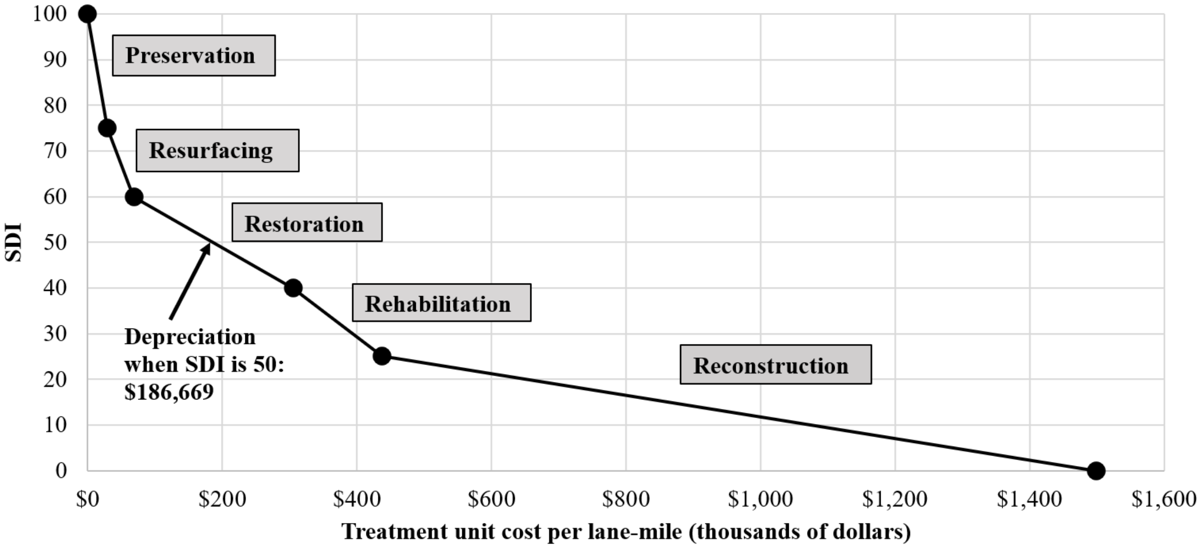
Project-Level and Network-Level Parameters

The research team calculated parameters for each year in the analysis period for each pavement segment and for the entire pavement network for all the PMS runs. Following are some of the parameters:

- Replacement cost: The replacement cost was calculated using the unit cost for the complete reconstruction of the entire pavement segment.
- Depreciation: An asset value depreciation calculation model was established, based on discussions with ITD, because the ITD PMS did not calculate depreciation. The model follows a simple piecewise linear depreciation approach. Pavement value depreciation is tied to the projected pavement condition at each year in the analysis determined by the performance models programmed in the PMS. Depreciation in each pavement segment was approximated as the cost of the treatment(s) required to restore the pavement to (or close to) as-built condition (SDI for flexible and OCI for rigid). Figure 11 and figure 12 illustrate sample depreciation calculations.
- Depreciated replacement cost: Depreciated replacement cost was calculated as the difference between the replacement cost and the accumulated depreciation.
- Treatment type mapping to FHWA work types: ITD had mapped all its pavement and bridge treatments to the FHWA work types during the development of its TAMP

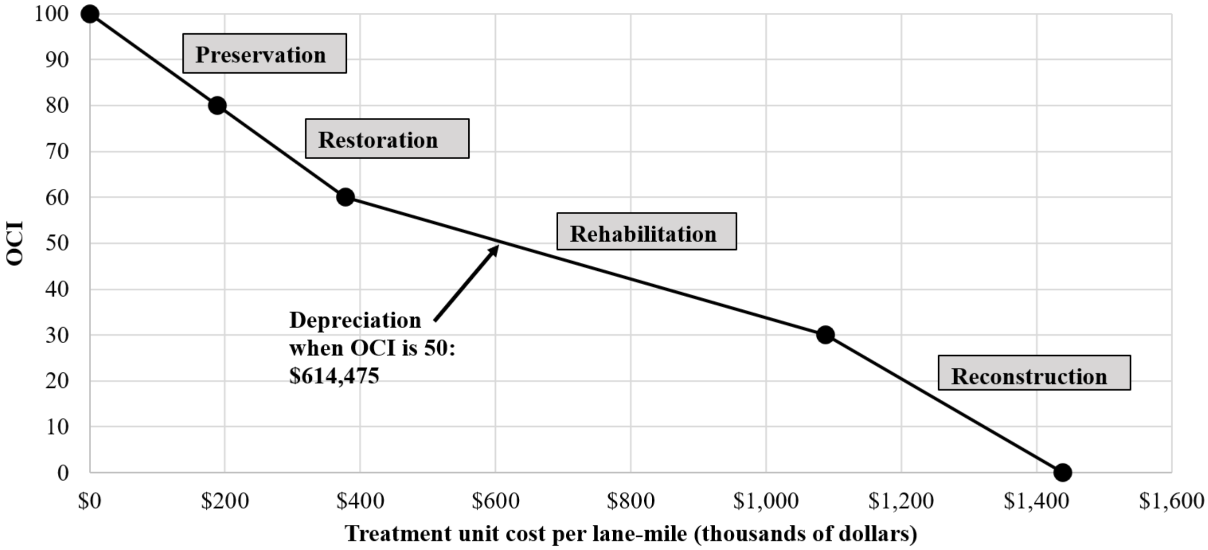
(ITD 2022). A summary of the treatment mapping from ITD treatments to FHWA work types is provided in appendix B.

- Pavement Need: This additional parameter is the annual funding level required to meet the desired SOGR. Estimating this parameter is a crucial step in calculating the ASI and ASR. For ITD, the functional desired SOGR reflected an overall pavement network in upper Fair condition (OCI ≥ 73). Meanwhile, the structural desired SOGR reflected an overall structural condition of the pavement network where the need for major treatments (restoration, rehabilitation, and restoration) was greatly diminished (SDI ≥ 75). The PMS output showed that annual budgets of $85 and $130 million failed to meet the established desired SOGR over the long term, whereas an annual budget of $200 million met the desired SOGR. Further analysis revealed that the $200 million analysis run did not result in complete utilization of the available budget in some years of the analysis period. The results from each of the three analysis runs were used to develop a regression model that helped to establish the pavement need for each year over the 40-year analysis period.



Source: FHWA.

Figure 11. Graph. Depreciation calculation model for flexible pavements—ITD.



Source: FHWA.

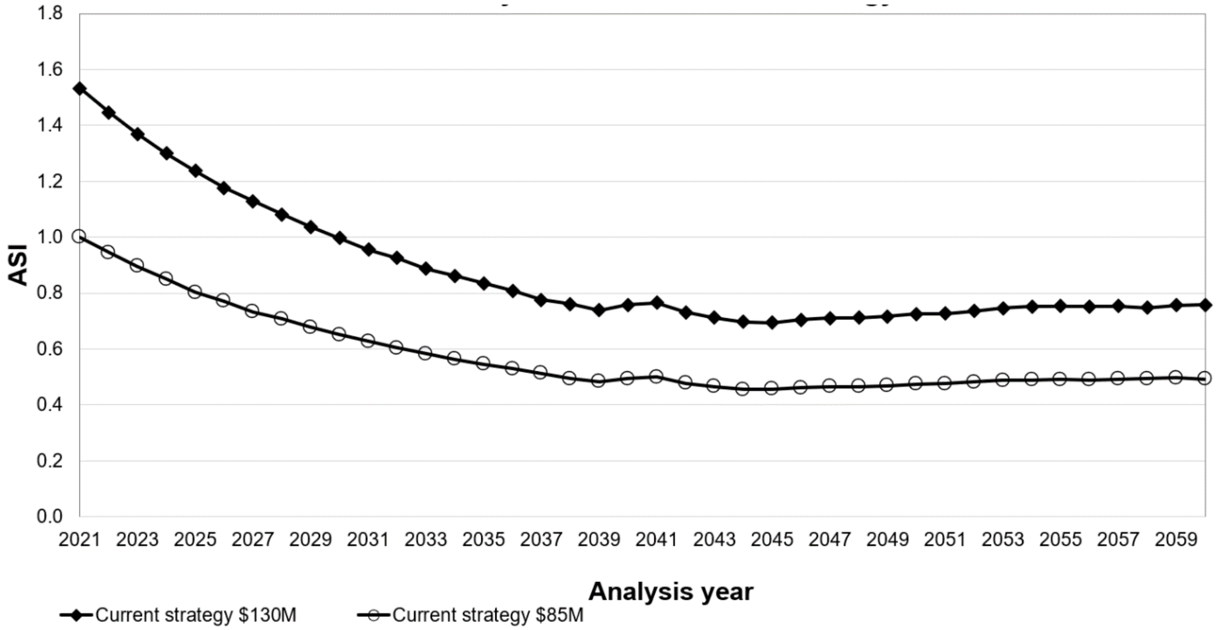
Figure 12. Graph. Depreciation calculation model for rigid pavements—ITD.

Financial Performance Measure Results

As part of the NGPPM validation, the research team calculated four financial measures using the pavement data from the PMS runs using the annual budget levels of $85 million and $130 million. This section presents analysis results and inferences from the calculation of these financial measures.

Asset Sustainability Index

ASI is an indicator of the adequacy of planned investments when compared to the pavement need. Figure 13 illustrates the ASI trends over the 40-year analysis period.



Source: FHWA.

Figure 13. Graph. Network-level ASI trends over the 40-year analysis period.

The following are a few key takeaways from the ASI projections:

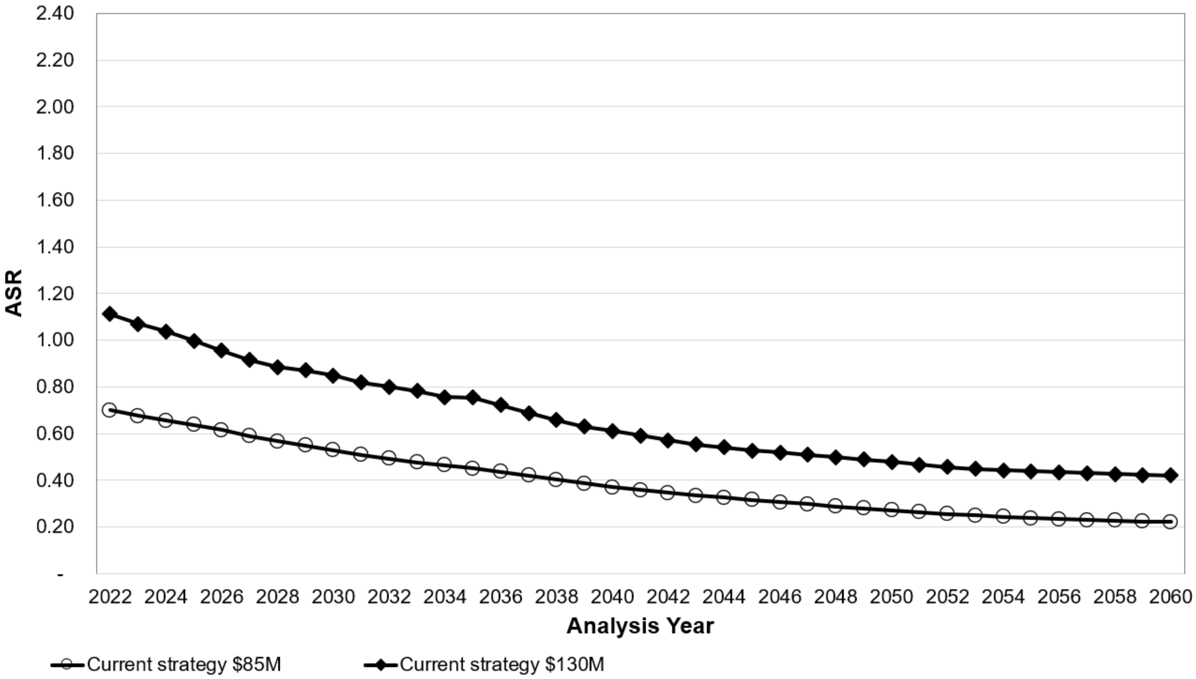
- The current annual funding level of $130 million is adequate to meet the desired SOGR over the first 10 years. The budget levels appear to be more than what is needed over this time (ASI greater than one). However, the apparently high ASI values are likely due to high SDI and OCI values at the start of the analysis. The research team hypothesized the high values resulted from an aggressive seal-coating program several districts in Idaho adopted over the last several years. The seal coats have the potential to mask structural distresses for a short duration of time. Frequent application of seal coats can also result in an artificially high pavement condition rating because the pavement data collection equipment can only capture surface conditions.

- The pavement need gradually increases, from $85 million annually at the beginning of the analysis to approximately $175 million annually starting at year 2035. This significant shift in the pavement need over the 15-year period is indicative of the fact that a vast majority of the system needed major intervention (e.g., rehabilitation, reconstruction). Preservation activities alone cannot sustain the pavement network over the long-term.

- The trends indicate ITD should consider a potential shift in pavement treatment strategies between 2027 and 2030 when the ASI starts approaching the 1.0 threshold because the ASI drops below one at Year 2030 for the $130 million budget. This proactive approach can potentially offset the rate of asset value depreciation over the long-term and provide a better return on investment to ITD.

Asset Sustainability Ratio

ASR is an indicator of whether the planned investments are adequate to offset asset value depreciation (Ram et al. 2023). Figure 14 illustrates the ASR trends over the 40-year analysis period.



Source: FHWA.

Figure 14. Graph. Network-level ASR trends over the 40-year analysis period.

A few key takeaways of the ASI projections are as follows:

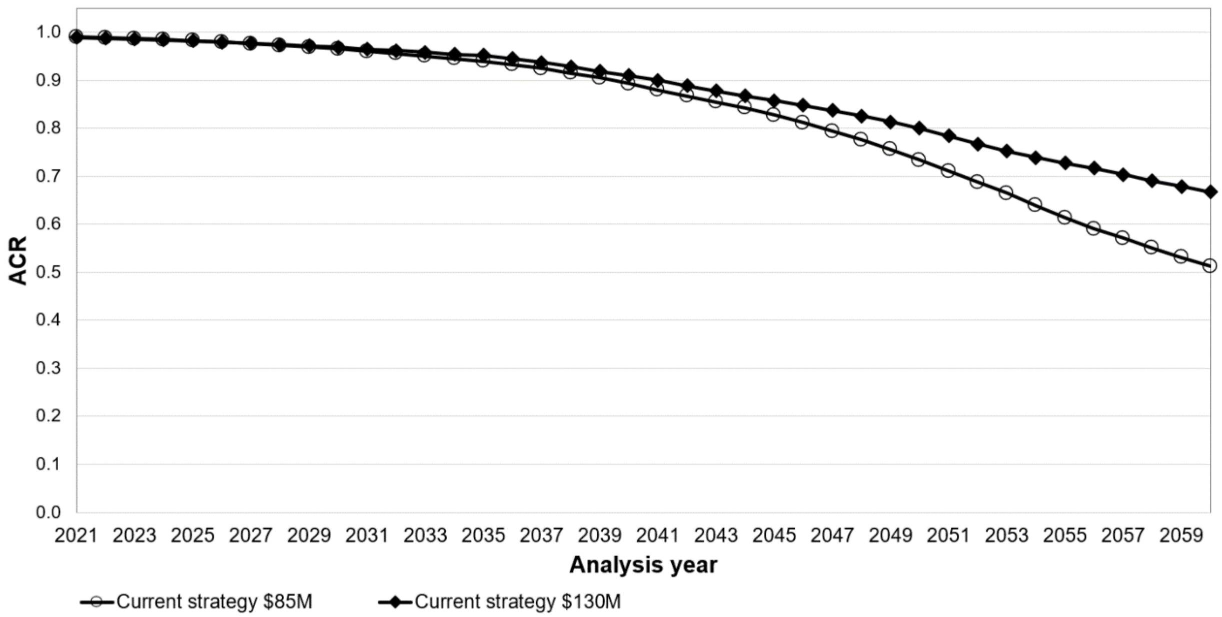
- ASR trends indicate the current annual budget of $130 million is not adequate to offset the asset value depreciation, even over the first 10 years of the analysis. By 2030, the ASR for the $130 million analysis run drops to 0.7, and by 2040, the values decline further to 0.4. As such, ITD should consider a treatment strategy change before 2030 to effectively offset asset value depreciation. Proactive investments in heavier treatments are likely required for ITD to be able to sustain the value of their pavement network over the long-term.

- The projection indicates a strategy shift 15–20 years in the future might be too late, resulting in an appreciable impact on the value and condition of the pavement network. A sudden increase in the ASR is noted at year 2035. This increase corresponds to an increase in the amount of rehabilitation and reconstruction investments, particularly on several rigid pavement segments in Poor condition. However, this investment does not result in a significant impact over the long-term as the ASR continue to decline.

- The research team inferred a reduced budget level of $85 million is simply inadequate to maintain ITD's pavement network even over the first 10 years, as the ASR plummeted to 0.4 within the 10-year time horizon.

Asset Consumption Ratio

ACR indicates the average proportion of as-new, or as-built, condition left in the system (Ram et al. 2023). Figure 15 illustrates the ACR performance measure's trends over the 40-year analysis period.



Source: FHWA.

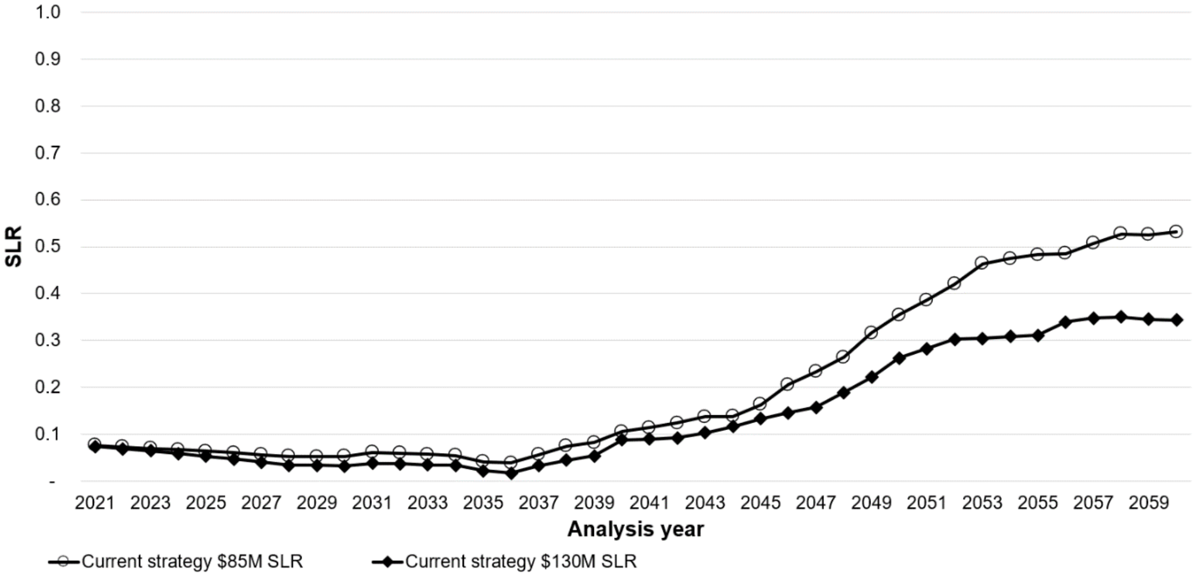
Figure 15. Graph. Network-level ACR trends over the 40-year analysis period.

A few key takeaways of the ACR projections are as follows:

- The ACR trends resemble the pavement condition trends illustrated in figure 10 closely. For the first 20 years, the ACR values are at or above 0.9. The high value is primarily due to the way the performance measure is calculated. The large denominator value (replacement value of the pavement network) results in the measure having a decreased sensitivity to depreciation or investments, compared to the other measures.
- The $130 million budget level yields an ACR of just below 0.67 at the end of the analysis period. Meanwhile, the $85 million budget level results in an ACR of about 0.5. Notably, the ACR at the end of the analysis period are comparable to the OCI values—61 and 45 for the $130 million and $85 million budget levels, respectively. Although the ACR trends offer no new insights into the pavement management decisionmaking process, the agreement between OCI and ACR trends over the long analysis period indirectly validates the approach used to calculate the ACR.

Stewardship Liability Ratio

The SLR is an indicator of the proportion of unfunded pavement management treatment selections when compared to the replacement value of the pavement network (Ram et al. 2023). Figure 16 illustrates the SLR trends over the 40-year analysis period.



Source: FHWA.

Figure 16. Graph. Network-level SLR trends over the 40-year analysis period.

A few key takeaways of the SLR projections are as follows:

- The SLR plot will be a vertically reflected trend over the horizontal axis when compared to the OCI trend. This trend is expected since higher pavement condition levels typically result in smaller amounts of unfunded treatment needs, especially in the early years when the available funding appears to be adequate to maintain the system at or above the desired SOGR.

- The SLR plot illustrates how an agency will be unable to eliminate its treatment backlog altogether, according to realistic and reasonable expectations. In the case of ITD, the agency was willing to accept a maximum SLR of 10 percent. The SLR trends reflect that both funding levels resulted in SLR of less than 10 percent until year 2036, after which the SLR begins to increase. The rate of change is significantly higher for the $85 million analysis run, especially from year 2045. The SLR trends suggest that ITD should consider investing in more significant treatments before 2035. To keep the backlog growth rate in check, the pavement treatment strategy change would potentially need to occur at least 3 to 5 years before SLR values start to increase. This finding is consistent with the results reported for the ASI and ASR performance measures.

Proposed Transportation Asset Management Methodology

Pavement Data Preprocessing

The proposed TAMM validation was performed using the TA-MAPO tool. This tool requires the pavement data to conform to a specific format, as specified in a pavement candidate file (FHWA 2024b). Therefore, a major task in the validation process was the identification of the necessary pavement data elements from the PMS data output file to map to the pavement candidate file (appendix B). Once the key data elements were identified and mapped, the research team was able to generate the pavement candidate file for the analysis. The following are some key considerations and assumptions made during the analysis:

- The LCC calculation used a 40-year analysis period even though the TA-MAPO tool only analyzed 10 years of treatment suggestions.

- The agency benefit was based on reducing the LCCs of managing the pavement network. Agency savings were calculated as the difference in LCCs between strategies where a treatment is deferred by 1 year.

- A pavement user cost of zero was assumed, as there was no suitable approach to calculate user costs at the network level using ITD's PMS.

- The safety and mobility performance outcomes were assigned a default value of 100, as they were not direct outputs from the PMS.

- The maintenance cost savings were built into the LCC calculations, so they were not provided as separate input for the TA-MAPO tool.

- The TA-MAPO tool offered documentation for pavement condition in terms of *%Good* and *%Poor* (FHWA 2024b). To obtain these parameters, pavement condition values were converted to Good (OCI > 80), Fair (60 ≤ OCI ≤ 80), and Poor (OCI < 60). The assumptions made as part of this conversion process are described in appendix E.

Bridge Data Preprocessing

Since the bridge work candidates were generated by StruPlan, preprocessing consisted of preparing the received ITD data for StruPlan and extracting data from the model results. ITD provided the data in the form of text files exported from the agency's BMS. The text files were already structured in the format needed by StruPlan (Thompson 2021). Certain diagnostics and corrections were performed, as follows:

- Checks for element and environment classifications conforming to ITD metadata.

- Removal of element inspection rows corresponding to defect records. These rows provide added detail in the bridge inspection process, but they are not used in deterioration modeling or LCCA.

- Conversion of inspection dates between spreadsheet formats.

- Cross-referencing of element records with element-level deterioration and cost data to ensure that models were provided for all relevant ITD elements.

In addition to these steps, StruPlan contains a large set of additional error checks and conversions to ensure that valid results can be computed for every bridge, even in cases where data values are missing. These checks and conversions are documented in the StruPlan user manual (Thompson 2021).

The calculations provided by StruPlan are complex, reflecting the wide diversity of structure types and concerns that exist in any State's bridge inventory. On each bridge, elements are grouped according to similarity of material and deterioration rates and associated with protective elements, if any, such as wearing surfaces, coatings, and sealed expansion joints. A long-term cost analysis is conducted for each possible condition state of each element group, analyzing the first 75 years individually and subsequent years as a perpetuity. ITD specified a 2-percent real discount rate for the analysis. As part of the StruPlan analysis, functional characteristics of each bridge are compared with LOS standards to classify bridges as *Sufficient* or *Deficient* for safety and mobility. Work candidates are developed for each bridge for each of the first 10 years, estimating the initial cost, the 10-year performance outcome, and the benefit in terms of avoided social cost. Social cost is the sum of agency, user, and nonuser costs. Work candidates are generated for the do-nothing, preservation, rehabilitation, or reconstruction treatments, but only the alternative with the least long-term social cost is carried through for programming. Appendix E provides more detail on the calculations.

The table of work candidates prepared by StruPlan has the same general layout as the TA-MAPO assets worksheet, with one row per bridge and 10 columns of work candidates representing the 10 years of the tradeoff analysis. Bridge work candidate data were copied and pasted from StruPlan to the TA-MAPO tool to add to the pavement data already compiled.

StruPlan further processes its work candidates to enable a tradeoff analysis that is similar to the TA-MAPO tool's analysis but focuses only on structures. Table 10 shows a tabular example of a performance forecast in StruPlan.

Table 10. Tabular example of StruPlan performance forecast for bridges.

Year	Good Condition (percent)	Poor Condition (percent)
2020	28.35	3.42
2021	27.56	3.44
2022	26.70	3.63
2023	26.57	3.68
2024	26.43	3.70
2025	26.37	3.86
2026	26.76	3.74
2027	26.39	3.78
2028	25.75	3.89
2029	25.11	3.96
2030	24.31	4.04
Targets	35	5

Figure 17 shows a graphical example of a performance forecast in StruPlan. The examples use the ITD-specified fiscal scenario with a first-year cost of $80 million. Funding is assumed to grow at the same rate as inflation to maintain constant buying power in this scenario. The funding was sufficient to maintain a nearly steady health index (weighted average of element conditions) but was not enough to keep Federal performance measures constant. This situation is typical of the early years—after the emphasis on preservation has increased—because preservation often focuses on protective elements that are not considered in the Federal performance measures.

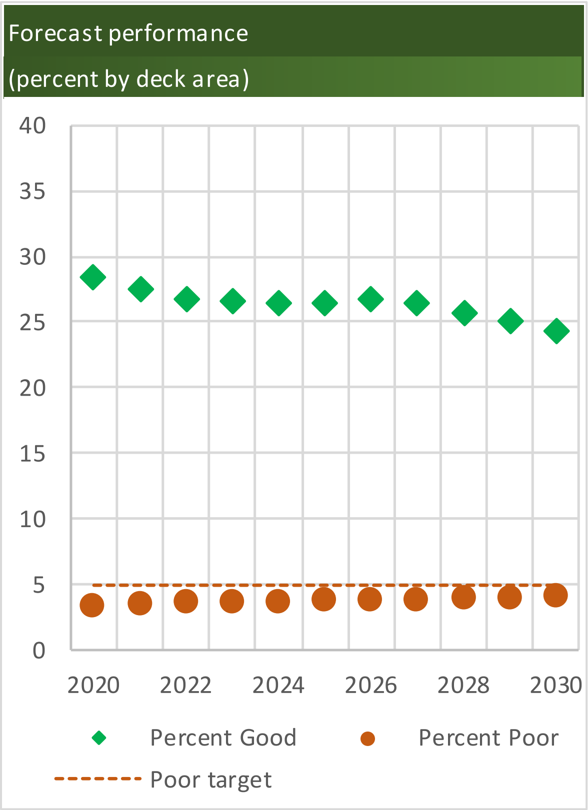
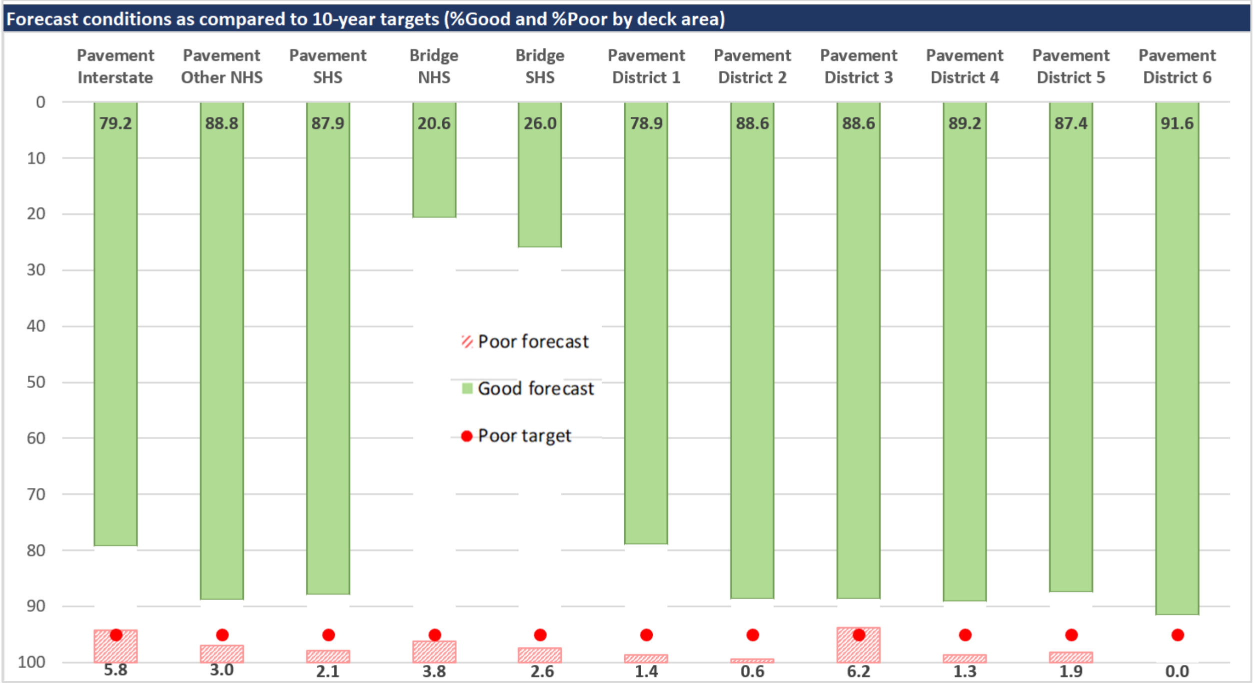


Figure 17. Graph. Graphical example of StruPlan performance forecast for bridges for ITD.

Cross-Asset Tradeoff Analysis and Results

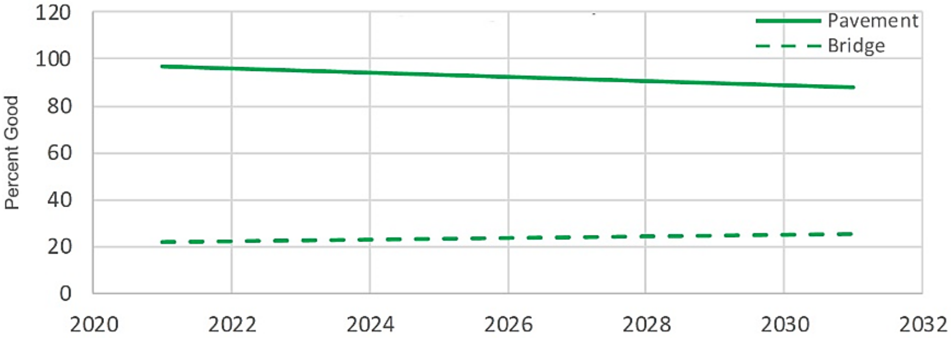
The TA-MAPO tool provides a graphical representation comparing the 10-year forecast performance against specified targets for any defined subsets of the network. Figure 18 shows an example from the ITD pilot study. In this case, ITD elected to focus on *%Poor* and did not specify targets for *%Good*. In this scenario, bridge conditions satisfied the *%Poor* targets for the NHS and SHS. Pavement conditions for most subnetworks satisfied the targets, except for the interstates and District 3, which slightly exceeded their *%Poor* targets. The targets worksheet in the TA-MAPO tool enables an agency to modify targets or give any part of the network additional weight in an attempt to improve performance. When funding is held constant, giving more weight to one part of the network reduces the relative weight given to the rest of the network. The TA-MAPO tool is especially useful for investigating that type of tradeoff (FHWA 2024b).



Source: FHWA.

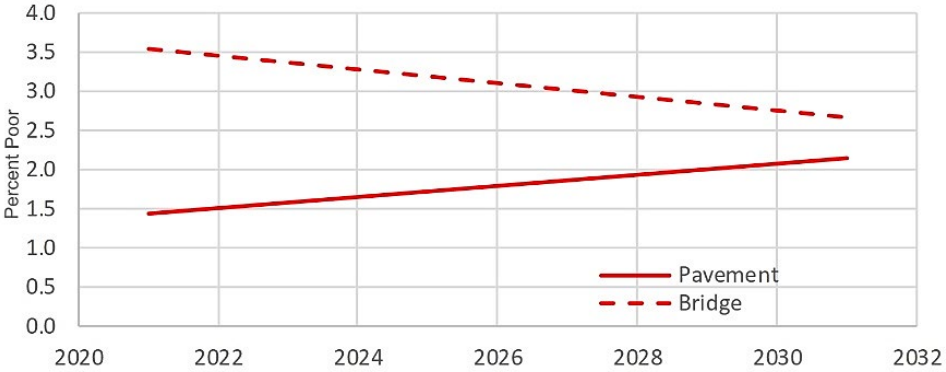
Figure 18. Graph. TA-MAPO tool comparison of forecasted conditions and 10-year targets.

The research team observed that Idaho's pavements appeared to be in considerably better condition than its bridges, although both categories compared favorably with National standards, as is demonstrated by the funding allocation analysis (figure 19). The graphs in figure 19 show that using the same benefit-cost prioritization measure for both pavements and bridges tends to move their conditions closer together; in this case, bridge conditions improved at the expense of pavement conditions.



Source: FHWA.

A. Changes in Good conditions.

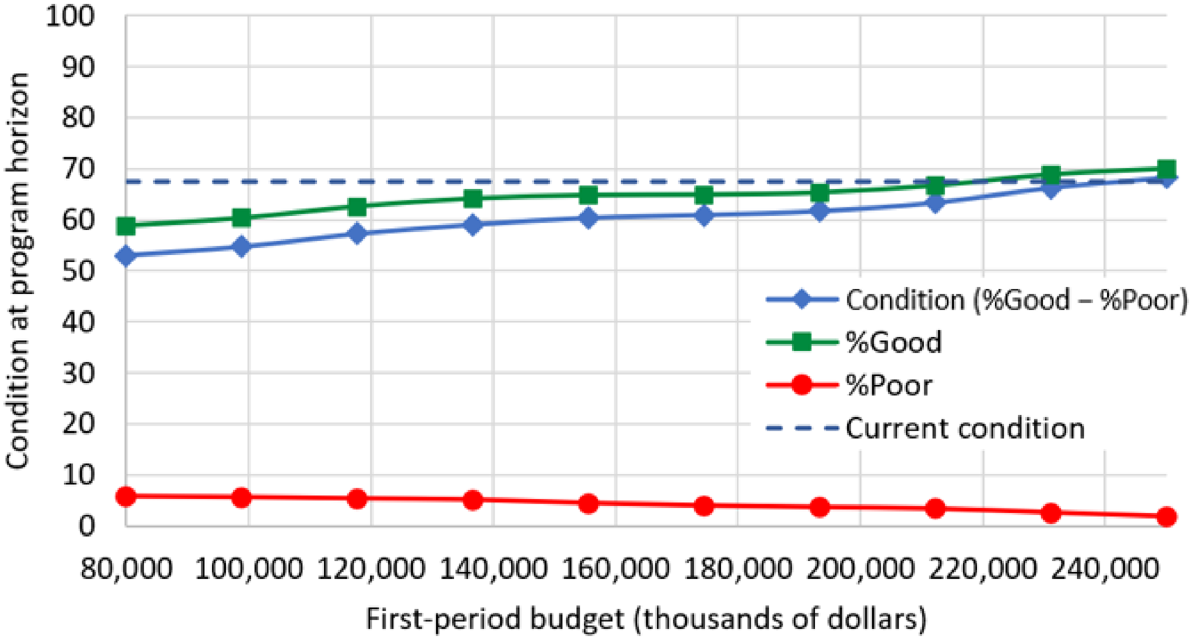


Source: FHWA.

B. Changes in Poor conditions.

Figure 19. Graphs. Changes in ITD's pavement and bridge conditions.

Decisionmakers often find it intuitive that an increase in funding for infrastructure renewal should result in better conditions. The TA-MAPO tool has a worksheet geared toward evaluating this tradeoff quantitatively (FHWA 2024b). Figure 20 shows an example of the improvement in NHS condition that may result from an increase in funding for pavements and bridges. When interpreting this graph, pavement and bridge measures are combined in a weighted average by replacement value. This metric is calculated differently from the Federal performance measures, which weight pavements by lane-miles and bridges by deck area. Also note that the standards used in defining Good and Poor are fundamentally different for pavements and bridges. Therefore, the graph gives a general impression of the relative effect on performance but does not directly forecast a Federal measure.



Source: FHWA.

Figure 20. Graph. Funding versus condition for pavements and bridges combined.

CHAPTER 6. SOUTH DAKOTA VALIDATION STUDY

VALIDATION PROCESS

South Dakota was the second State selected for pilot validation of the NGPPMs and proposed TAMM. As with the Idaho validation, the project team held a kick-off meeting with SDDOT representatives to introduce team members, review the project, discuss the goals and expectations of the study, and identify any foreseeable challenges. Based on the results of this meeting, the project team developed a preliminary work plan and schedule to help guide validation efforts. They then revised the work plan as needed to better accommodate SDDOT's pavement and asset management practices and data. The following are some key changes the research team made to the work plan to tailor it to SDDOT:

- The use of treatment-specific decision trees and performance models that take into consideration pretreatment pavement conditions allowed SDDOT's PMS to generate all feasible pavement lifecycle treatment strategies for each segment included in the network. The detailed output from this multistrategy analysis is not typically available to the PMS user; only the information for the "selected" strategy (i.e., the strategy with the highest BCR based on the established budget) for a given segment is available. For the validation study, SDDOT was able to work with the PMS vendor to extract the required multistrategy analysis data.

- The use of network-level data was anticipated for the RSI validation. However, because the PMS required substantial computational times for a 30-year multistrategy analysis run, the project team opted to use pavement data from a small roadway corridor for the NGPPM validation.

- The validation of TAMM analyzed the impact of delaying the suggested treatment by 1 year at a time over the chosen analysis period for each pavement and bridge segment included in the analysis. Since SDDOT's PMS generated all feasible treatment strategies, the project team was able to use the outputs from the multistrategy analysis to generate the inputs for the TA-MAPO tool used in the TAMM validation efforts.

Next-Generation Pavement Performance Measures

During the kick-off meeting, SDDOT expressed great interest in investigating the advantages and disadvantages of using the NGPPMs and comparing the results of the lifecycle strategy generated through the RSI analysis to the lifecycle strategy selected by the PMS. To accomplish this objective, the research team gathered and analyzed SDDOT's pavement management data, conducted the RSI analysis, and computed four financial NGPPMs (ASI, ASR, ACR, and SLR) (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). The research team then provided suggestions to SDDOT on how the measures could potentially be used to enhance existing business processes. Following is a brief description of the steps involved in the validation process:

1. Determine data needed for analysis and review relevant supporting documentation: The research team compiled a list of SDDOT's data needs for computing the performance measures included in the validation effort. Additionally, key SDDOT documents (e.g., 2019 TAMP, 2020 PMS synopsis) were obtained and reviewed to help identify the

parameters that would be involved in the calculation of the performance measures (SDDOT 2019, 2023).

2. Review PMS analysis capabilities: The research team reviewed these capabilities thoroughly while working in close coordination with SDDOT's pavement team. The research team then identified a list of analyses that needed to be conducted with the PMS to enable NGPPM calculation.

3. Conduct PMS analyses: SDDOT's pavement team conducted PMS analysis runs that served as input to the calculation of the NGPPMs. The PMS vendor supported SDDOT and the research team in extracting outputs from the PMS not typically available to the user.

4. Calculate NGPPMs: The research team developed a simple calculation tool to compute the NGPPMs of interest to SDDOT. This tool used the PMS analysis results from step 3 for the calculations.

Proposed Transportation Asset Management Methodology

SDDOT officials were introduced to the proposed tradeoff analysis methodology through a series of workshops conducted in the summer of 2020. As with the Idaho validation, the research team acquired detailed pavement and bridge data from SDDOT and then entered them into the TA-MAPO tool to analyze tradeoffs among costs and conditions across asset classes and subnetworks. A separate spreadsheet model was used to accumulate PMS data and calculate the performance measures from multiple analytical runs. Additionally, the StruPlan spreadsheet program was used to generate candidates for bridge work. These candidates were then combined with pavement work candidates to form the investment candidate file used in the TA-MAPO tool.

DATA AND INFORMATION GATHERING

This section presents details on the data and information-gathering efforts for the performance measure validation process.

Data for the Next Generation Pavement Performance Measure Validations

Initial Data Request

The research team held several web meetings with the FHWA panel and SDDOT staff to identify the information necessary for the validation process (appendix C). As a result of these meetings, the research team requested and obtained the datasets and documentation from SDDOT.

Financial Data

SDDOT provided information on their current pavement budget level over a 30-year analysis period.

TAMP Document (SDDOT 2019) and Enhanced PMS Synopsis Document (SDDOT 2020)

The TAMP document described SDDOT's asset management practices and pavement performance measures and targets. The synopsis described SDDOT's PMS's elements and capabilities. On review of these documents, the research team identified the following items for use in calculating the NGPPMs:

- SDDOT treatment categories and descriptions: The SDDOT treatment categories were mapped to the four FHWA work types: maintenance, preservation, rehabilitation, and reconstruction (refer to appendix C for details).
- Pavement performance indicators: The SDDOT pavement management decisions are based on individual distress ratings and a calculated composite index called the surface condition index (SCI) (Chang et al. 2020). SCI values range from 0 (poor condition) to 5 (excellent condition) and are derived in different ways based on pavement type (flexible, rigid, and gravel) and functional class (urban and rural), as follows:
    - The SCI is based on the extent and severity of transverse cracking, fatigue cracking, patch deterioration, block cracking, roughness, and rut depth for rural flexible pavements.
    - The SCI is based on the extent and severity of transverse cracking, fatigue cracking, patch deterioration, block cracking, and rut depth for urban flexible pavements.
    - The SCI is based on the extent and severity of punchouts, block cracking, and roughness for rural and urban continuously reinforced concrete (CRC) pavements.
    - The SCI is based on the extent and severity of corner cracking and joint spalling for rural jointed concrete pavements.
    - The SCI is based on the extent and severity of corner cracking, faulting, and joint spalling for urban jointed concrete pavements.
    - The SCI is determined with a conversion of the gravel rating determined from the distress survey crew to a five-point scale for gravel pavements.

Pavement Management System Analysis Output Files

SDDOT provided sample PMS analysis output files for the research team to review as part of the initial data request. The following is a summary of the key data fields SDDOT provided in their PMS output files:

- Description of pavement segment (pavement segment name, roadway name, pavement type, size (centerline miles), location, functional class, and number of lane-miles).
- Suggestions for 30-year treatment (treatment type and cost).
- Condition of pavement (in terms of SCI).

Additional Data Request

The research team worked closely with the SDDOT pavement management staff to gather all the necessary parameters needed for the validation study. This coordination was achieved through a series of web meetings with SDDOT staff to finalize the parameters and strategies to be used in the validation effort, summarized as follows:

- Analysis Period: 30 years.
- Real discount rate: 3.32 percent.
- Annual budget level: $16.7 million.
- Performance target: Weighted average SCI of 3.7.
- Analysis corridor: US-14 (rural minor arterial road with 118 segments and 579 lane-miles).
- Annual budget levels evaluated:
  - Current budget level.
  - Current budget plus 20 percent.
  - Current budget minus 20 percent.
  - Unlimited budget (no budget constraint).

To conduct the RSI analysis, the research team also requested that SDDOT provide the outputs from the PMS's multistrategy analysis of all the lifecycle strategies for the US-14 corridor.

Additionally, SDDOT provided a PMS output file covering a 30-year analysis period for each PMS run requested. Although the PMS runs were conducted using a 30-year analysis period, the performance measure validation efforts only considered the results from the 25-year period.

Data for Transportation Asset Management Methodology Validation

Pavement Data

The ability of SDDOT's PMS to conduct a multistrategy analysis made it conducive for generating inputs for the TA-MAPO tool. However, the generated strategies are not based on delaying treatments by 1 year at a time. Since the TA-MAPO tool required data from strategies where the suggested treatments are delayed 1 year at a time over the chosen analysis period, the research team had to manually adjust the strategies generated by the PMS to generate the inputs in a format that was compatible with the TA-MAPO tool. The PMS analysis also included the results of a do-nothing strategy and a maintenance-only strategy, and these results were used as inputs to the TA-MAPO tool. Although the TA-MAPO tool conducts the analysis over a 10-year period, the PMS analysis was conducted for a 30-year analysis period to evaluate the long-term impact (in terms of change in LCC) of delaying treatments (FHWA 2024b).

To generate inputs for the TA-MAPO tool, the research team requested that SDDOT run a multistrategy analysis over the entire pavement network. SDDOT provided the PMS output file from the multistrategy analysis covering a 30-year analysis period.

Bridge Data

As with the Idaho validation, the AASHTOWare BrM software was unable to generate the necessary bridge data for tradeoff analysis in a timely and cost-effective manner (AASHTO 2023). Thus, the StruPlan open-source spreadsheet was used with various configurations made for incorporating SDDOT planning metrics, such as deterioration rates, unit costs, and fiscal assumptions. Appendix E and the StruPlan user manual discuss this spreadsheet in more detail (Thompson 2021).

To facilitate the StruPlan analysis, SDDOT provided text files containing appropriate tables from its BrM database in July of 2020 (Thompson 2021; AASHTO 2023). The dataset included all NHS bridges and all State-owned bridges—a total of 1,803 structures. Like the Idaho validation, the dataset included data about each bridge, data about the roadway carried by the bridge, and data from the most recent bridge inspection. In general, all the data items provided could also be found in annual submittals to FHWA's NBI and complied with FHWA's Coding Guide (FHWA 2023, 1995).

VALIDATION ANALYSES AND RESULTS

This section presents results of the South Dakota NGPPM and proposed TAMM validation efforts.

Lifecycle Performance Measures

The NGPPM validation efforts focused on the following three lifecycle measures:

- RSI: Identification of the optimal lifecycle treatment strategy that results in the lowest practical LCC while meeting the established performance requirements and budget constraints.
- CAR: Ratio of the costs of a given lifecycle strategy to the costs of an optimized lifecycle strategy. Two forms of CAR were calculated in the validation effort—short-term accrual ratio and long-term accrual ratio.
- AUCR: Ratio of the programmed annualized unit cost (EUAC per lane-mile) to the optimized annualized unit cost.

Remaining Service Interval Approach

Under SDDOT's current optimization approach, the PMS identifies and selects the treatment strategy with the highest BCR for a given budget level. However, the LCCs are not explicitly considered while evaluating the treatment strategies generated by the PMS. Thus, the selected strategy may or may not be the optimal strategy from a lowest LCC perspective.

Under the RSI approach, the research team used the outputs from the multistrategy analysis to generate several alternative lifecycle strategies that met the established performance requirement (SCI ≥ 3.7) and LOS threshold (IRI ≤ 130 inches/mi[24]). Two alternative RSI strategies were evaluated, as follows:

- RSI-unconstrained (RSI-U): Lowest LCC strategy in the absence of any budget constraints.
- RSI-constrained (RSI-C): Lowest LCC strategy with the current budget level established for the US-14 analysis corridor.

The research team compared the RSI-U and RSI-C strategies using the following analysis runs in SDDOT's PMS:

- Maximum benefit at current budget (MBCB): Analysis run at current budget level.
- MBCB+20: Analysis run at 20-percent higher budget level.
- MBCB−20: Analysis run at 20-percent lower budget level.
- Maximum benefit at unlimited budget (MBU): Analysis run with no budget constraints.

Data Preprocessing for Lifecycle Performance Measure Validation

A major part of the lifecycle measure calculation process was the identification of the necessary data elements from the PMS data output files (appendix C). Once the key data elements were identified, the research team analyzed several parameters used to compute the lifecycle measures.

Pavement Condition Trends

The temporal pavement condition trends were analyzed by plotting the annual network-level weighted average conditions (based on SCI, weighted by lane-miles) over the 25-year period (figure 21). As can be seen, the condition trends can be divided into two distinct zones. In zone 1, which extends from year 0 through year 7, the pavement condition constantly declines, from a starting SCI value of about 4.2 (even for the unlimited budget strategy). The pavements are generally above the established SCI target, so the deteriorating conditions in this zone are primarily due to the lower investment levels. In zone 2, which extends from year 8 through year 25, the conditions mostly improve. As expected, better pavement conditions are achieved with an increased budget, with the MBU strategy resulting in immediate significant improvements at year 8.

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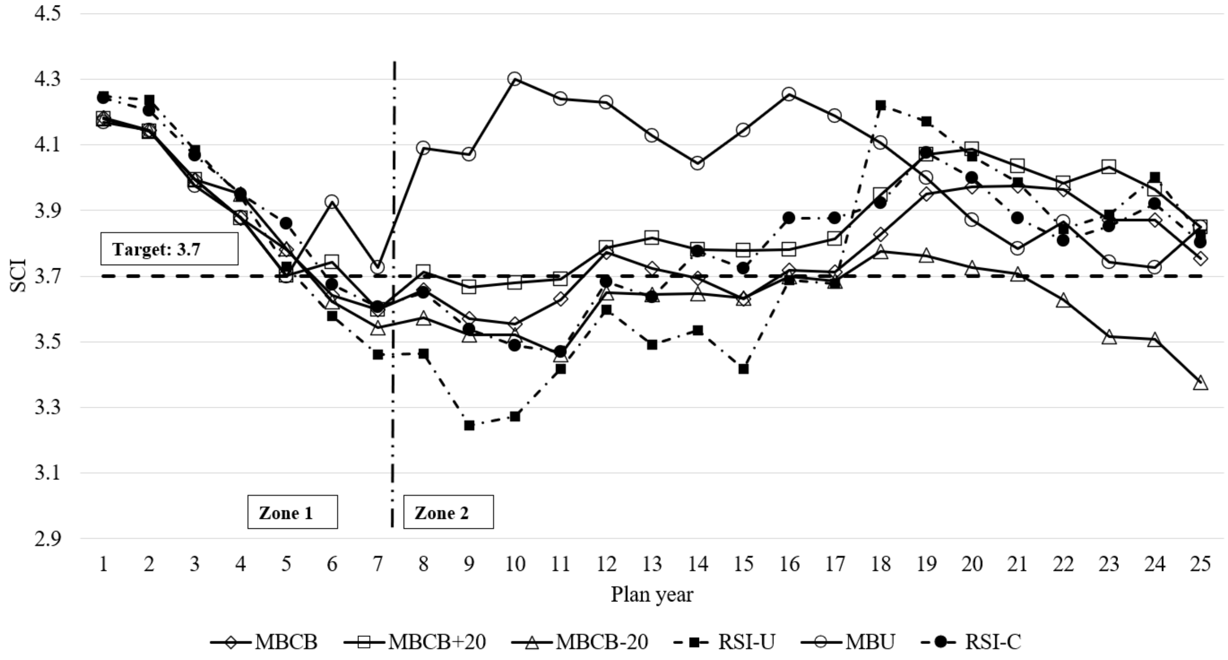
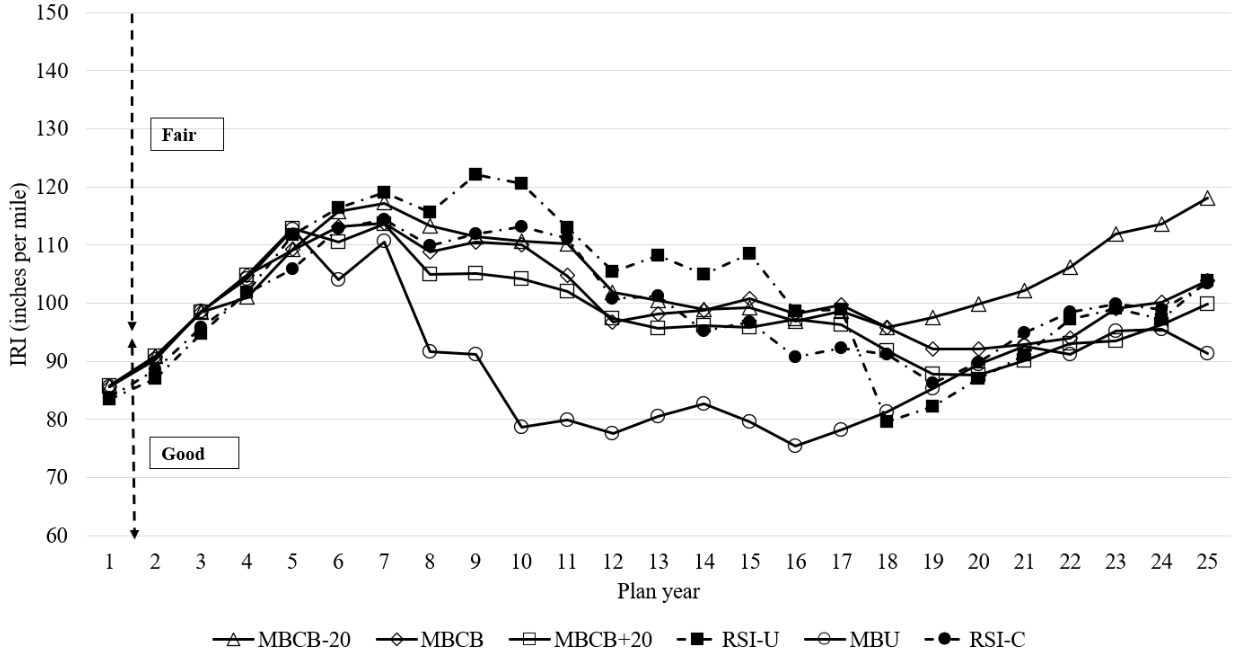
[24] Established based on the midpoints of the thresholds for low (95 inches per mi) and high (170 inches per mi) IRI values after discussion with SDDOT.



Source: FHWA.

Figure 21. Graph. Pavement condition trends for the strategies evaluated—SDDOT.

The pavement conditions for all the other strategies fall below the established condition target between year 7 and year 11, and then they tend to improve. At the end of year 25, the MBCB−20 strategy (20-percent budget reduction) is the only one that results in a network-level SCI that is significantly lower than the established performance target. Figure 22 shows the IRI trends for each strategy evaluated. As can be seen, all the strategies successfully maintained IRI values below 130 inches per mi over the 25-year analysis period. Based on the performance thresholds established under FHWA's National Highway Performance Program, these levels of roughness correspond to Good (IRI < 95 inches per mi) or Fair (IRI 95–170 inches per mi) conditions, as per 23 CFR 490 (CFR 2016a).



Source: FHWA.

Figure 22. Graph. IRI trends for the strategies evaluated.

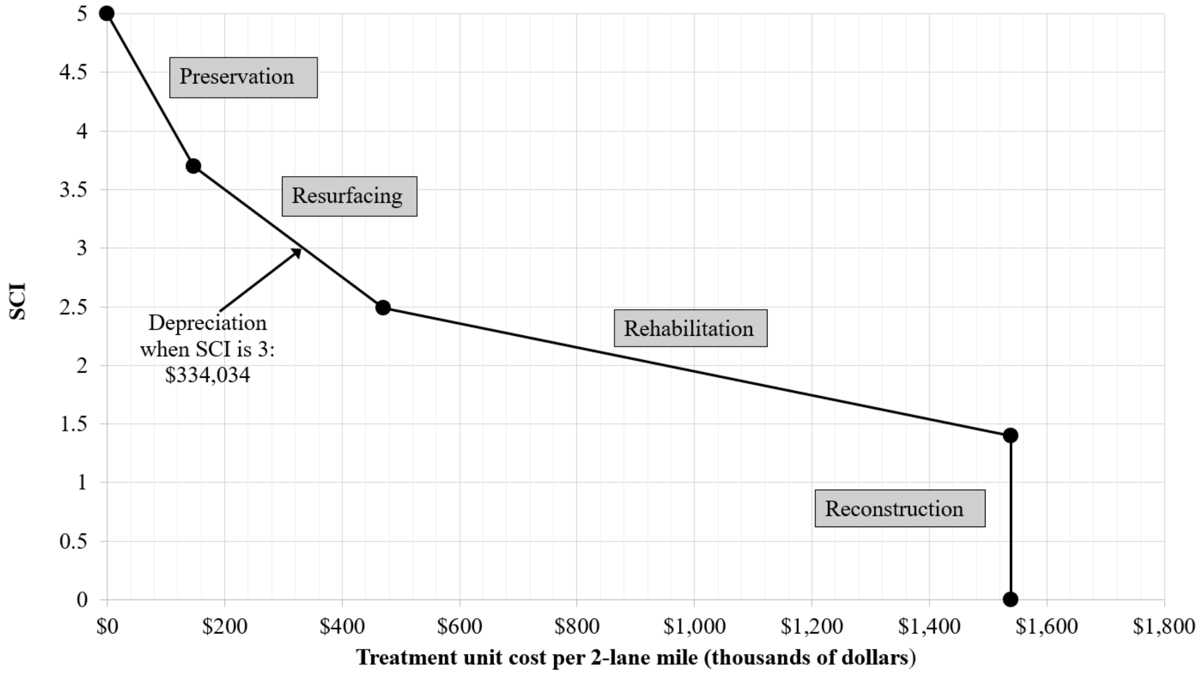
Cost-Related Parameters

For all the PMS runs, the research team calculated the following parameters for each year in the analysis period for each pavement segment and the entire pavement network:

- Depreciation: An asset value depreciation calculation model was established based on discussion with the SDDOT pavement management team since the SDDOT PMS did not calculate depreciation. The model follows a simple piecewise linear depreciation approach. Pavement value depreciation is tied to the projected pavement condition (SCI) at each year in the analysis determined by the performance models used in the PMS. Then, the depreciation in each pavement segment is approximated to be the cost of treatment(s) required to restore the condition of the pavement close to an as-built condition. Figure 23 and figure 24 illustrate the depreciation model and sample depreciation calculations for flexible and rigid pavements, respectively.

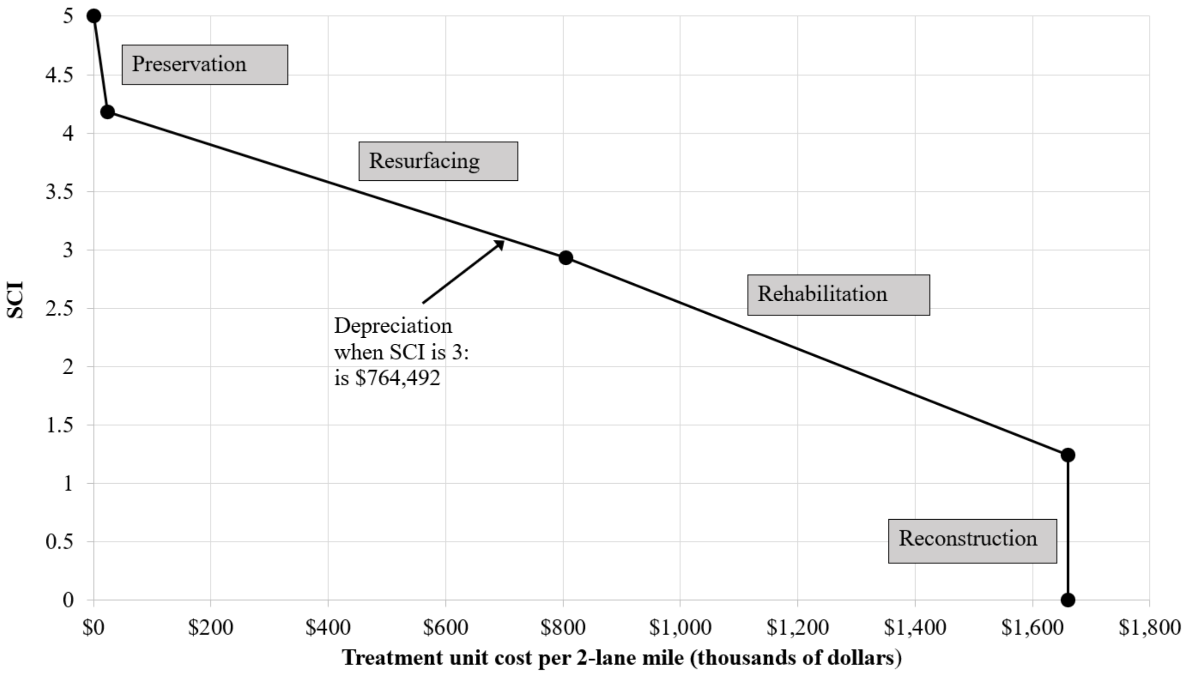
- Treatment cost present value (PV): Accounts for time value of the programmed investment decided by the PMS. The research team used a real discount rate of 3.32 percent to convert the treatment cost at each year of the analysis period to the base-year (2020) dollars.

- LCC: Calculated for each strategy using the following three approaches:
    - PV: This approach calculates LCC by aggregating the PVs of treatment costs over the 25-year analysis period.
    - PV + RV: This approach includes treatment cost PVs and treatment RVs when their service lives extend beyond the end of the analysis period. A simple straight-line model is used to determine the RV. The estimated service life of each treatment category used in the analysis is summarized in table 11.
    - PV + cost to restore: This approach adds the cost to restore the condition of the pavement segment close to the as-built condition (calculated using the depreciation models) at the end of the analysis period to the PV of treatment costs over the 25-year analysis period.



Source: FHWA.

Figure 23. Graph. Depreciation calculation model for flexible pavements—SDDOT.



Source: FHWA.

Figure 24. Graph. Depreciation calculation model for rigid pavements—SDDOT.

Table 11. Assumptions regarding treatment service life.

Treatment	Service Life (years)
Preservation	5
Resurfacing	8
Restoration	10
Reconstruction—Flexible	18
Reconstruction—Rigid	33

Lifecycle Performance Measure Results

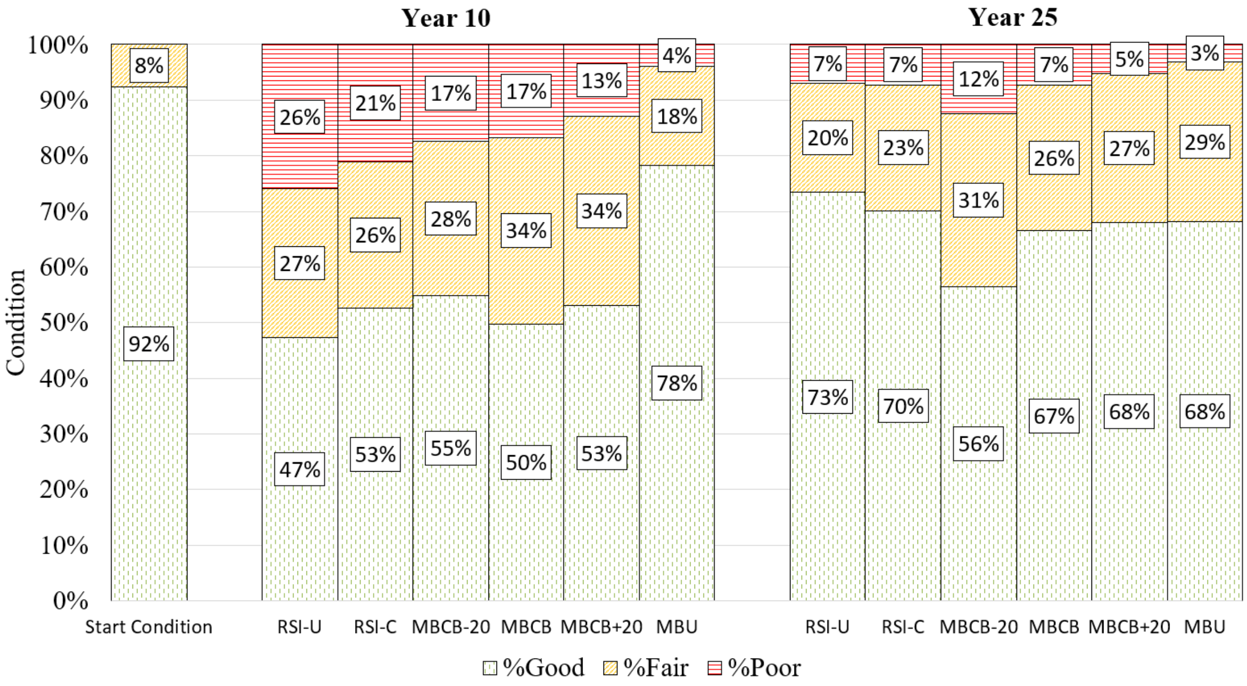
Two lifecycle performance measures (CAR and AUCR) were calculated using the results from the RSI analysis.

Remaining Service Interval Analysis

The results of the PMS analyses at the four budget levels (MBCB, MBCB+20, MBCB−20, and MBU) were compared to the two strategies (RSI-U and RSI-C) generated using the RSI analysis. Comparisons were also made in terms of future pavement conditions, annual variation in treatment cost, LCC, and the effect of different discount rates.

Figure 21 presented a comparison of the pavement condition trends for each strategy evaluated indicating the short-term (10-year) and long-term (25-year) Good/Fair/Poor condition outcomes for each strategy. For this analysis, condition was delineated by the following SCI ranges: Good ($3.4 \leq SCI \leq 5.0$), Fair ($2.1 \leq SCI < 3.4$), and Poor ($SCI < 2.1$).

Figure 25 illustrates the conditions at the start of the analysis and the conditions achieved at year 10 and year 25 for each of the six strategies evaluated. As can be seen at the start of the analysis, 92 percent of the pavements are in Good condition, and the remaining 8 percent are in Fair condition.



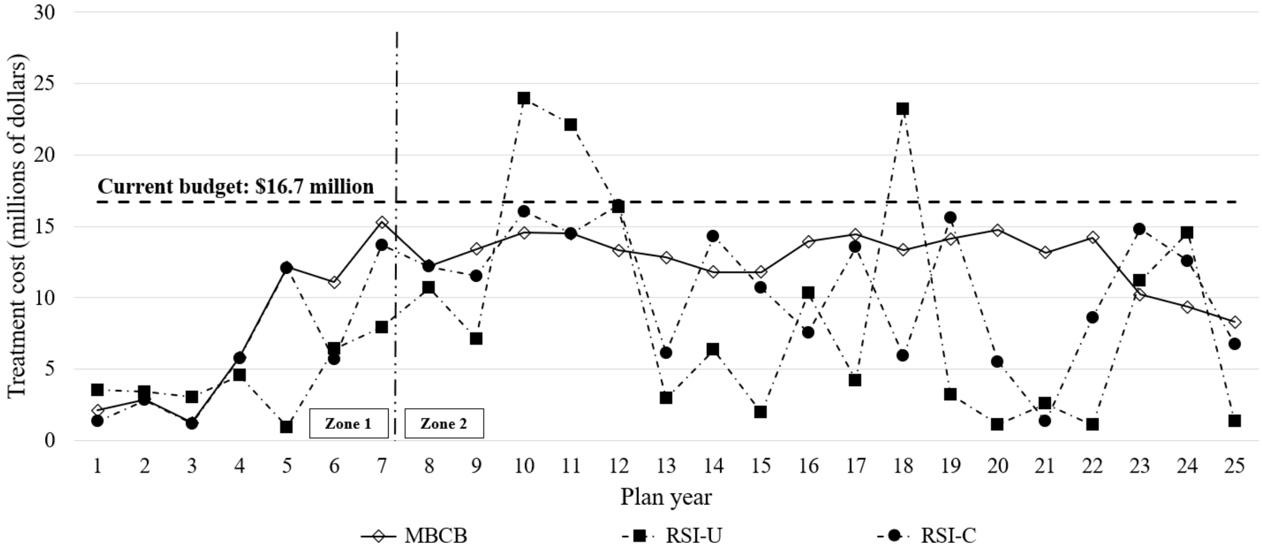
Source: FHWA.

Figure 25. Graph. Short- and long-term condition outcomes.

At year 10, the strategies with higher budget levels resulted in better conditions, as expected. The MBU strategy resulted in 96 percent of the pavements in Fair or better condition while the MBCB+20 strategy resulted in 87 percent of the segments in Fair or better condition. The MBCB and MBCB−20 strategies resulted in 83 percent of the pavements in Fair or better condition, while the RSI-C strategy resulted in 79 percent of the network in Fair or better condition. Lastly, the MBCB strategy yielded a slightly better outcome (Fair or better condition) than the constrained RSI analysis.

The condition outcomes at year 25 are considerably different from the 10-year outcomes, further emphasizing the importance of considering a longer analysis period. The condition outcomes from RSI analysis-based strategies (RSI-U and RSI-C) are quite comparable to the MBCB strategy, with each strategy resulting in a 93-percent Fair or better condition.

Figure 26 shows the annual variation in treatment cost for the MBCB, RSI-C, and RSI-U strategies. The annual treatment cost for the RSI-U strategy exceeded the established annual budget level in year 10, year 11, and year 18. Hence, an RSI-C strategy that met established budget constraints was developed. Figure 26 clearly demonstrates that the MBCB strategy results in more uniform funding allocations between year 7 and year 25.

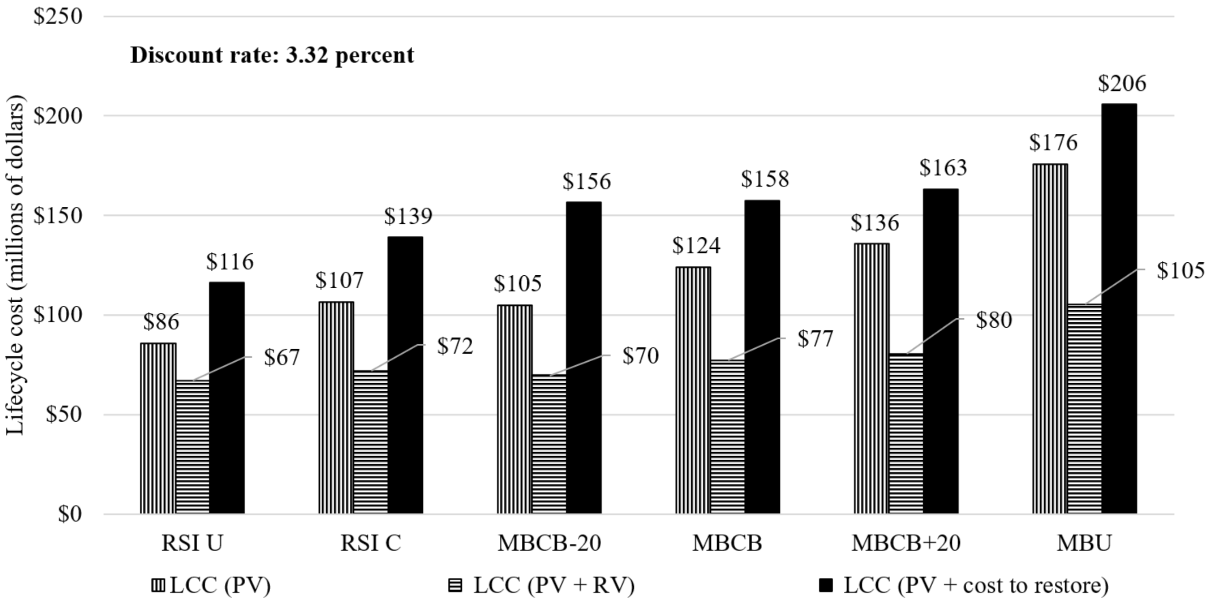


Source: FHWA.

Figure 26. Graph. Annual variation in treatment cost.

SDDOT's PMS appeared to optimize the treatment suggestions so that more uniform costs resulted over the analysis period. However, the RSI strategies were developed outside the PMS environment with the main objective of minimizing LCCs while meeting established performance requirements and LOS thresholds. Therefore, the treatment suggestions were not optimized to result in uniform treatment costs over the analysis period.

Figure 27 shows the LCCs calculated for each evaluated strategy.



Source: FHWA.

Figure 27. Graph. LCC comparison of the evaluated strategies.

The key findings from the LCC comparisons are as follows:

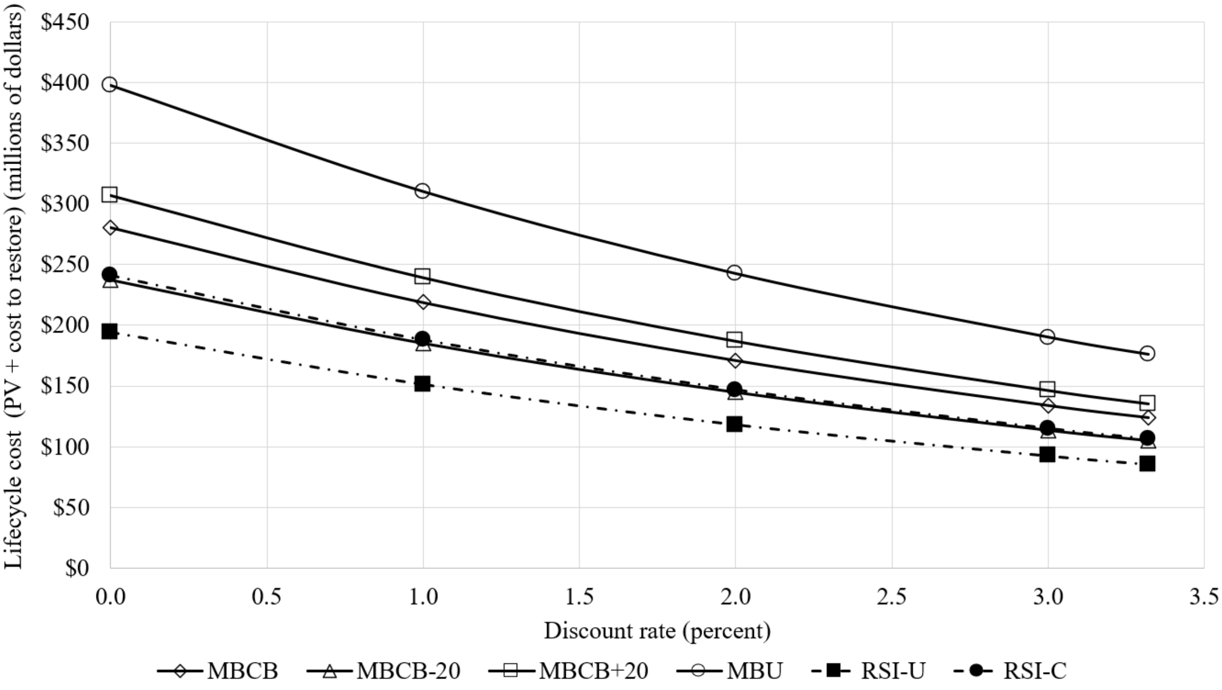
- The RSI-U strategy represents the lowest LCC strategy that meets established performance constraints in a fiscally unconstrained scenario. On the other hand, the MBU strategy generated by the SDDOT PMS resulted in the highest LCC.

- The LCC calculated using the PV + RV approach resulted in the lowest value when compared to the other two approaches, because the RV of treatments beyond the analysis period, which is a negative dollar amount, is included. The RV estimates for the strategies optimized using SDDOT's PMS were generally higher because the PMS triggered more reconstruction treatments (particularly in the later years) that had longer service lives.

- The constrained RSI strategy has a slightly lower LCC when compared to the MBCB strategy generated using the PMS. However, the differences are minor. The approach used by SDDOT's PMS resulted in outcomes that were similar to the lowest LCC strategy even though the analysis did not explicitly consider LCC in the optimization routine.

- The LCC of the RSI-C strategy is similar to the MBCB−20 strategy. However, the MBCB−20 strategy results in a significant decline in pavement condition after year 21. At the end of the analysis period, the SCI value drops to 3.38, which is below the established target.

The LCC values presented in figure 27 were calculated using a real discount rate of 3.32 percent. Figure 28 illustrates the impact of the discount rate on the LCC for each strategy evaluated. At a discount rate of 3.32 percent, the difference in LCC between the MBCB and RSI-C strategy is \$18 million. This difference increases to \$42 million when a discount rate of 0 percent is used. Because the discount rate can significantly impact the LCC, care should be exercised to choose appropriate values that are reflective of current market trends.



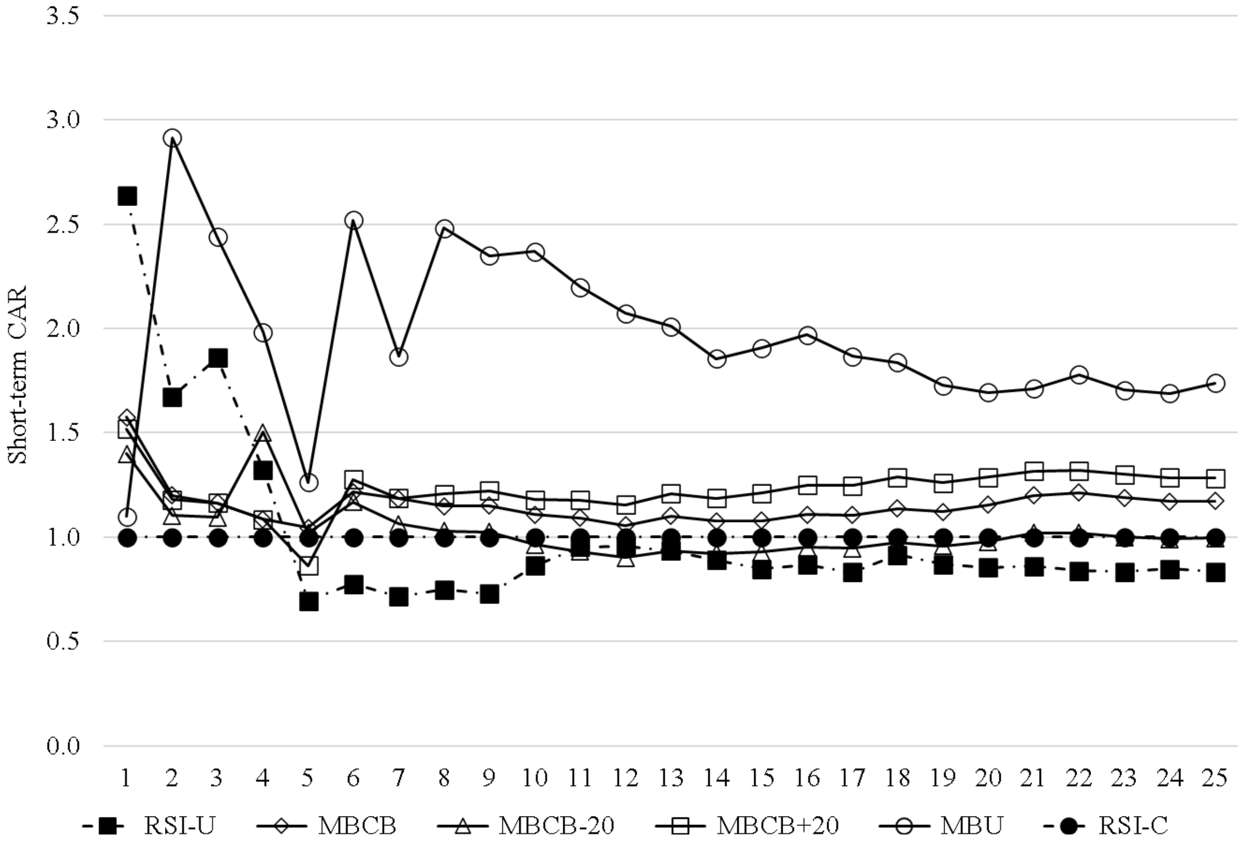
Source: FHWA.

Figure 28. Graph. Impact of discount rate on LCC.

Cost Accrual Ratio

For validation purposes, the research team calculated both short-term and long-term CAR values for each strategy. The RSI-C strategy was considered the optimal lifecycle strategy since it represented the lowest LCC strategy that met the established budget and performance constraints.

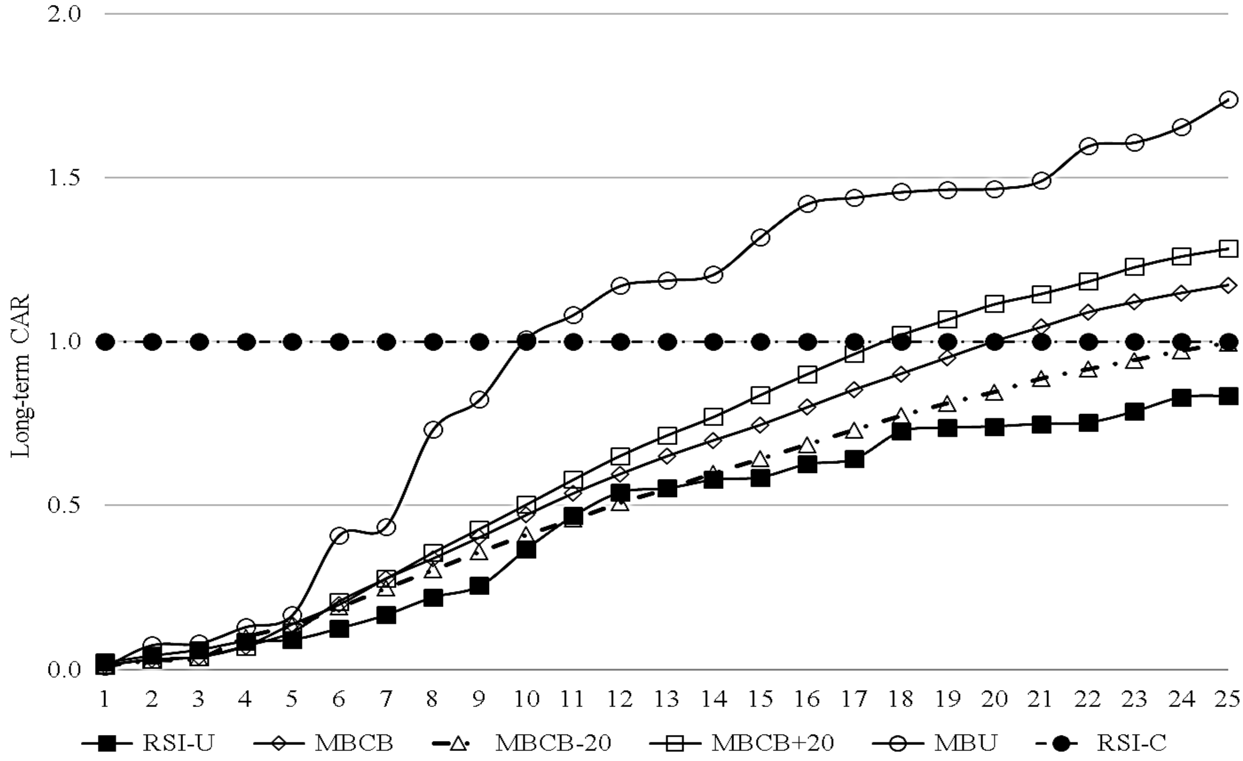
Figure 29 illustrates the variation in short-term CAR calculated for each strategy. As can be seen, all the strategies except MBU are fairly consistent with the optimized strategy in terms of investments made. In addition, while the RSI-U strategy shows significantly higher investments when compared to the RSI-C strategy over the first 3 years, the CAR values drop below one from year 5 onward. The RSI-U strategy represents the lowest LCC strategy; however, it does not meet the established annual budget constraints. Thus, it is not a practical strategy to consider, from an implementation standpoint. The MBCB−20 strategy exhibits CAR values that are similar to the CAR values for the RSI-C strategy; however, the performance levels achieved through the MBCB−20 strategy are noticeably lower.



Source: FHWA.

Figure 29. Graph. Short-term CAR trends.

The long-term CAR trends illustrated in figure 30 provide quick feedback on the number of years for each strategy to use 100 percent of the planned investments based on the optimized strategy. With the MBU strategy, the total planned investments based on the RSI-C strategy are spent in only 10 years; with the MBCB strategy, the same amount takes approximately 20 years to be invested.



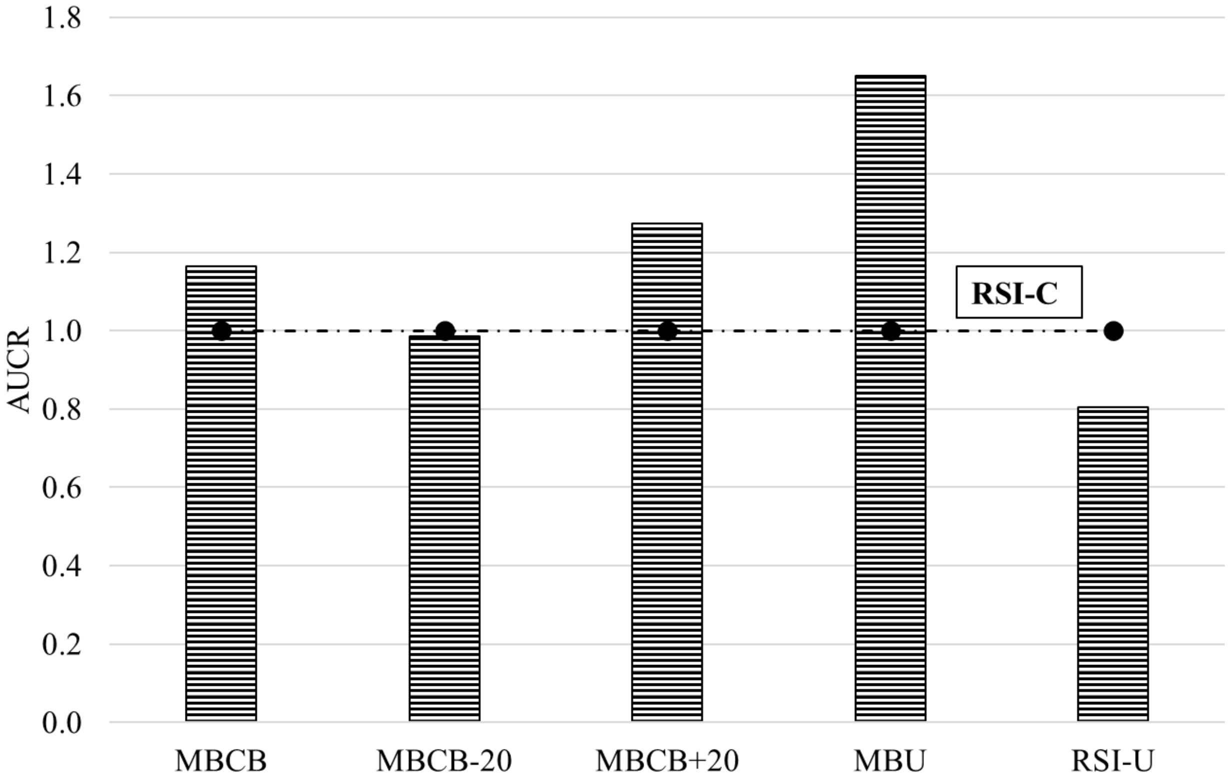
Source: FHWA.

Figure 30. Graph. Long-term CAR trends.

Annualized Unit Cost Ratio

The AUCR was calculated for each strategy using the programmed annualized unit cost and the optimized annualized unit cost. As with the CAR validation, the RSI-C strategy was considered the optimized lifecycle strategy; therefore, its AUCR value was 1.

Figure 31 shows the AUCR values calculated for each strategy over the 25-year analysis period. As can be seen, the AUCR for the MBCB strategy was almost 20 percent higher than the AUCR for the RSI-C strategy, and the AUCR for the MBCB+20 strategy was almost 30 percent higher than the AUCR for the RSI-C strategy.



Source: FHWA.

Figure 31. Graph. AUCR values for the lifecycle strategies evaluated.

Financial Performance Measures

The NGPPM validation also focused on the following four financial measures:

- ASI: The ratio of the planned investment to the budget needed to maintain the assets at the desired condition (Proctor, Varma, and Varnedoe 2012). The key parameter used in calculating the ASI measure is pavement need, which is the budget needed to maintain the network at the desired SOGR.

- ASR: The ratio of the investments to the depreciation under zero investment for a chosen fiscal period (Ram et al. 2023). The annual depreciation under zero investment was calculated by aggregating the annual depreciation and the pavement investment need. The pavement value depreciation was calculated based on the SCI value of the pavements.

- ACR: The ratio of the depreciated replacement cost to the current replacement cost (Ram et al. 2023).

- SLR: The ratio of the unfunded PMS treatments to the replacement cost of the pavement network (Ram et al. 2023). However, the unfunded treatment need/backlog is not a direct output from SDDOT's PMS analysis runs.

Data Preprocessing for Financial Measures Validation

A major part of the financial measure calculation process was the identification of the necessary data elements from the PMS data output files (appendix C). Once the key data elements were identified, several parameters used in computing the financial measures were then analyzed.

Pavement Condition Trends

Pavement condition trends over time were plotted and analyzed, as shown previously in figure 21.

Project-Level and Network-Level Parameters

The research team calculated parameters for each year in the analysis period for each pavement segment and for the entire pavement network for all the evaluated strategies. The following are some of the parameters:

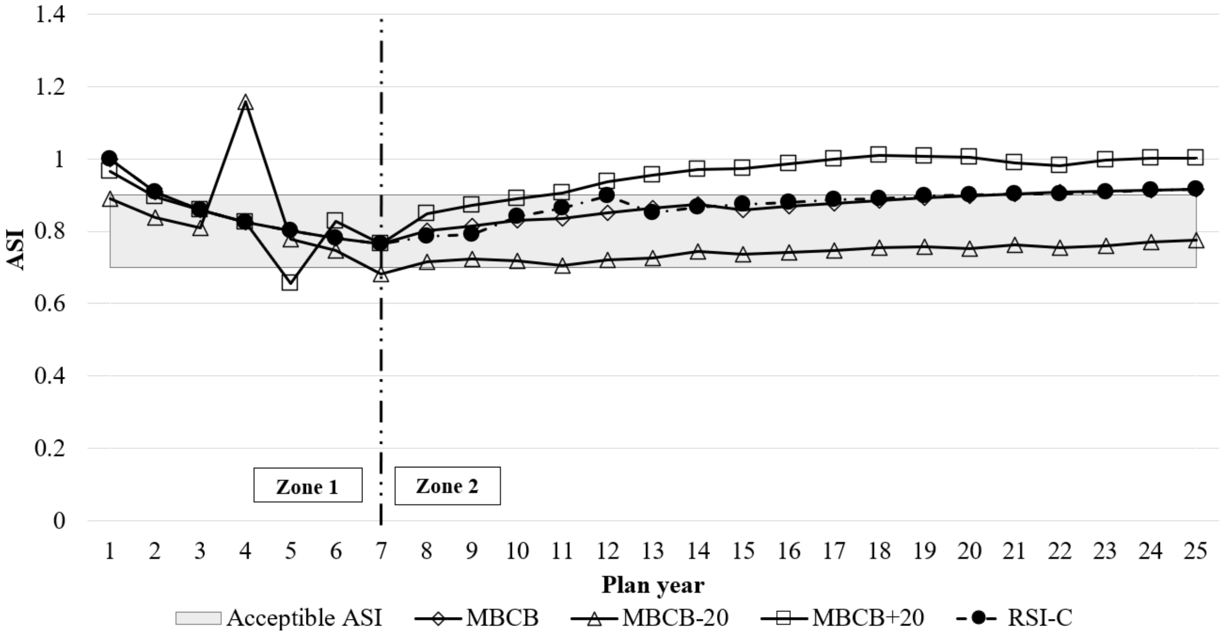
- Replacement cost: Calculated with the unit cost of complete reconstruction of the entire pavement segment.
- Depreciation: Calculated with a pavement value depreciation calculation model that was established based on discussions with SDDOT. (Figure 23 and figure 24 illustrated the flexible and rigid pavement depreciation models, respectively).
- Depreciated replacement cost: Calculated as the difference between the replacement cost and the accumulated depreciation.
- SDDOT treatment type: Mapped to FHWA work types based on discussions with SDDOT. The research team mapped all SDDOT's pavement and bridge treatments to the FHWA work types. A summary of the treatment mapping from SDDOT treatments to FHWA work types is provided in appendix C.
- Pavement need: This additional parameter is the annual funding level required to achieve and maintain the desired SOGR (target SCI of 3.7).

Financial Performance Measure Results

The financial measures were calculated using the MBCB, MBCB−20, MBCB+20, and RSI-C strategies created for this study. The following are results, inferences, and challenges from the analysis.

Asset Sustainability Index

Figure 32 shows the ASI trends over the 25-year analysis period. In zone 1, the ASI for all the strategies gradually decline due to lower investment levels in the first 7 years of the analysis. The investments in preservation and major rehabilitation begin to increase at year 8, and the ASI for all the strategies except MBCB−20 show a slight upward trend through year 17, after which they plateau. All the strategies generally indicated that an investment of at least 70 percent of the needs maintains the pavement at the desired SOGR.



Source: FHWA.

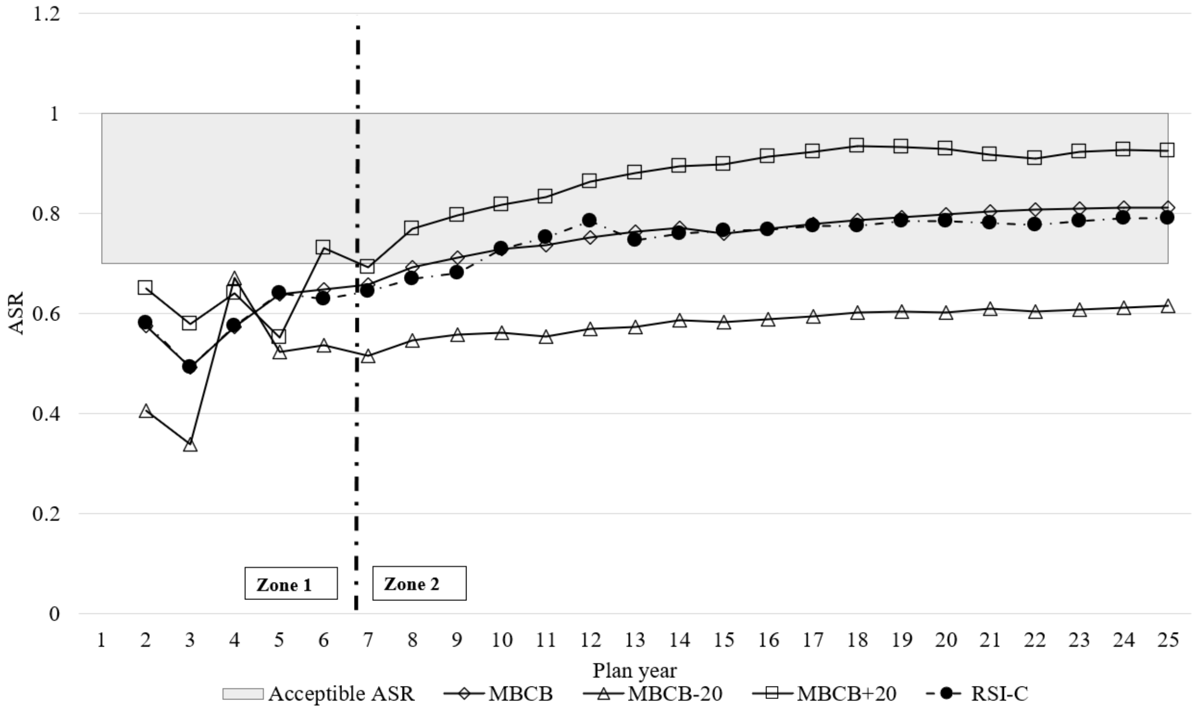
Figure 32. Graph. Network-level ASI trends over the 25-year analysis period.

At the end of the 25-year analysis period, the MBCB+20 strategy resulted in an ASI of 1, whereas the ASI for the MBCB and RSI-C strategies after this time was approximately 0.9. The MBCB−20 strategy was able to satisfy only 78 percent of the pavement needs and resulted in the pavement condition declining to 3.6. The other strategies resulted in SCI being maintained at approximately 3.8.

Asset Sustainability Ratio

Figure 33 illustrates the ASR trends over the 25-year analysis period. In zone 1, the planned investments were significantly lower than the needs and thus were not adequate to offset the depreciation accumulated in the first 7 years. However, with the significant increases in investments in zone 2, the ASR jumped above the 70 percent mark for all the strategies except the MBCB−20 strategy.

At the end of the 25-year analysis period, the MBCB+20 strategy resulted in the highest ASR (approximately 0.93). The ASR for the MBCB and RSI-C strategies after 25 years were close to 0.8, whereas the value for the MBCB−20 strategy was approximately 0.6. These projections indicate that, with a 20-percent reduction in the budget, SDDOT will only be able to offset 60 percent of the accumulated pavement depreciation.

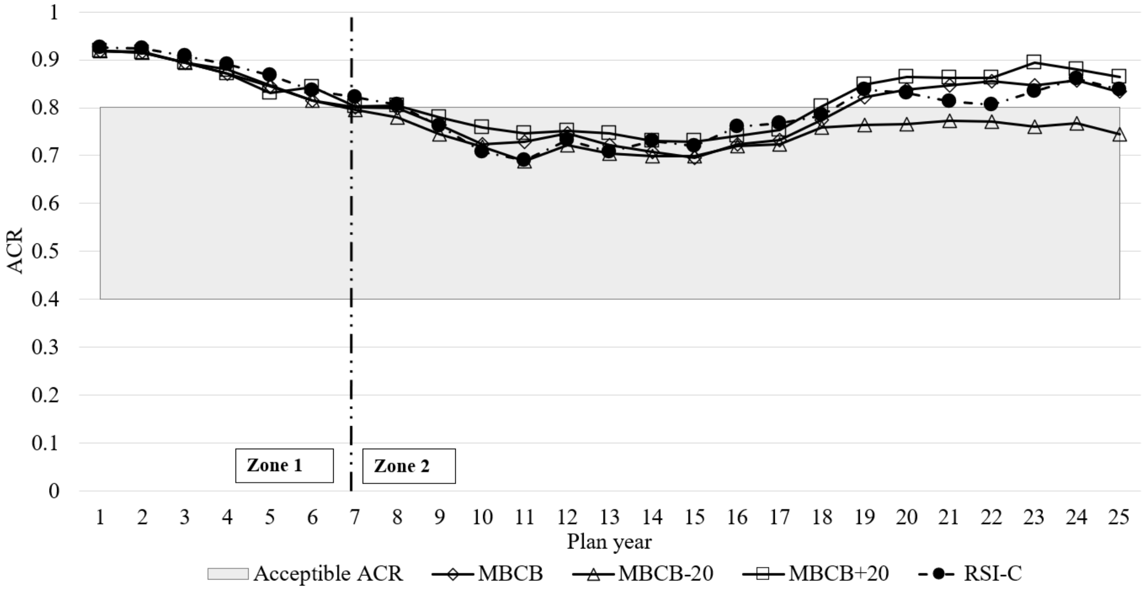


Source: FHWA.

Figure 33. Graph. Network-level ASR trends over the 25-year analysis period.

Asset Consumption Ratio

Figure 34 shows the ACR measure's trends over the 25-year analysis period. These trends are similar to the pavement condition trends illustrated previously in figure 21. The research team observed the ACR measure is not as sensitive to depreciation or investments as some of the other measures discussed earlier, since ACR compares asset value depreciation to the replacement value of the pavement network, which is a large value. All the strategies investigated were able to maintain an ACR of 70 percent or higher throughout the 25-year analysis period.



Source: FHWA.

Figure 34. Graph. Network-level ACR trends over the 25-year analysis period.

At the end of the analysis period, the MBCB, MBCB+20, and RSI-C strategies resulted in an ACR of approximately 0.84, while the MBCB−20 strategy resulted in an ACR of 0.74. These results are consistent with the findings from the lifecycle measure validation, where the MBCB−20 strategy, though similar to the RSI-C strategy in terms of LCC, resulted in a lower percentage of pavements in Fair or better condition.

Stewardship Liability Ratio

The SLR is the ratio of the unfunded pavement management treatment suggestions/backlog to the replacement value of the pavement network. However, backlog is not a direct output from the SDDOT PMS. Thus, the research team was unable to calculate the measure using the PMS analysis results.

The project team attempted to estimate the backlog with a different approach, using the MBU strategy analysis results generated by the PMS. Based on the assumption that there would be no unfunded treatment needs under the MBU strategy, the difference between the total investments under the MBU strategy and any given strategy was approximated to represent the total backlog. The annual backlog was then determined based on pavement condition trends over the 25-year analysis period. However, the SLR measure calculated using this approach did not result in any meaningful trends. Additionally, the approach used to estimate the backlog is data-specific and cannot be generalized for any analysis run conducted using SDDOT's PMS. Therefore, the SLR measure could not be validated using the outputs from SDDOT's PMS.

Notably, SDDOT's PMS does have an option to calculate the treatment backlog for each analysis run. However, that feature would need to be configured appropriately before the results can be used to compute and validate the SLR measure.

Challenges in Calculating Financial Performance Measures

A few key challenges during the financial performance measure validation efforts were faced.

- Small corridor pavement data: Although the use of analysis results based on the entire SDDOT pavement network would have been ideal for the performance measure validation efforts, a long-term multistrategy analysis run would have required exceedingly long computation times and a large dataset size. Nevertheless, it was attempted to conduct a long-term multistrategy analysis using the entire network's data, but the analysis run resulted in an error, which was possibly related to data size issues. Hence, it was decided to use data from a smaller pavement corridor for the analysis.

- Uneven annual investments: As illustrated previously in figure 24, the annual investment needs suggested by the PMS were significantly different in zones 1 and 2. Additionally, the PMS did not completely use the budget allocated. The use of a small pavement network to validate the performance measures could have resulted in uneven annual investment need suggestions from the PMS.

- Unfunded treatment needs unreported by the PMS: SDDOT's PMS did not have an explicit output for unfunded treatment needs due to budget constraints or treatment backlog. Alternate approaches to estimate the backlog were unsuccessful. Thus, the SLR measure could not be validated.

Proposed Transportation Asset Management Methodology

Pavement Data Preprocessing

As with Idaho's validation of the proposed TAMM, the research team performed a significant amount of data preprocessing to create a pavement candidate file for the TA-MAPO tool. This preprocessing included identifying the necessary pavement data elements from the PMS data output file and mapping them to the pavement candidate file (appendix C). Following are some of the research team's key considerations and assumptions from this effort (FHWA 2024b):

- The LCC was calculated with a 30-year analysis period even though the TA-MAPO tool only analyzed 10 years of treatment suggestions.

- The agency's main goal was based on the benefit of reducing the LCCs of managing the pavement network. Agency savings were calculated as the difference in LCCs between strategies where a treatment is deferred by 1 year. Several instances were identified that resulted in negative savings, indicating that deferring a treatment by 1 year resulted in a lower LCC.

- A pavement user cost of zero was assumed, as there was no suitable approach to calculate user costs at the network level using SDDOT's PMS.

- The safety and mobility performance outcomes were assigned a default value of 100, as they were not direct outputs from the PMS.

- The multistrategy analysis did not generate treatment suggestions for every year of the analysis period. However, for each pavement segment, the analysis provided a maintenance-only strategy and a do-nothing strategy. Therefore, a maintenance-only strategy was assumed for years where no treatments were triggered.

- The maintenance cost savings were built into the LCC calculations, so they were not provided as separate input for the TA-MAPO tool.
- The TA-MAPO tool will offer documentation for pavement condition in terms of *%Good* and *%Poor* (FHWA 2024b). To obtain these parameters, pavement condition values were converted to Good ($3.4 \leq \text{SCI} \leq 5.0$), Fair ($2.1 \leq \text{SCI} < 3.4$), and Poor ($\text{SCI} < 2.1$). The assumptions made as part of this conversion process are described in appendix E.

Bridge Data Preprocessing

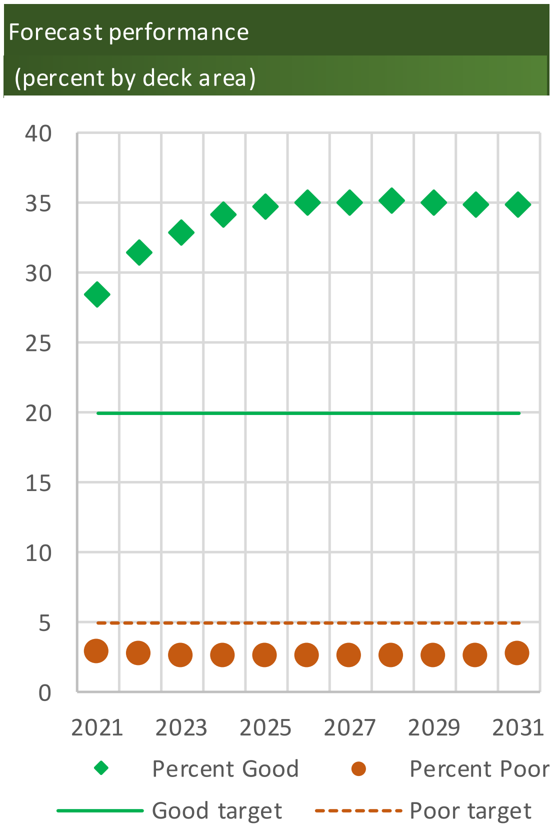
Since the bridge work candidates were generated by StruPlan, preprocessing consisted of preparing the received SDDOT data for StruPlan and extracting data from the model results. SDDOT provided the data in the form of text files exported from the agency's BMS. The files were already structured in the form needed by StruPlan. Certain diagnostics and corrections were performed, as follows:

- Checks for conformation of element and environment classifications to SDDOT metadata.
- Removal of element inspection rows corresponding to defect records.
- Cross-referencing of element records with element-level deterioration and cost data to ensure that models were provided for all relevant SDDOT elements.

As with the Idaho validation of the proposed TAMM, SDDOT specified the use of a 2-percent real discount rate in StruPlan to generate the bridge work candidates for the TA-MAPO tool. Table 12 and figure 35 show tabular and graphical examples, respectively, of a StruPlan performance forecast using the SDDOT-specified fiscal scenario with a first-year cost of $68.44 million. SDDOT specified a 4-percent inflation rate for bridge costs, representing an annual decline in buying power and no real growth. The funding was sufficient to increase the *%Good* performance measure to 34.88 percent after 10 years and reduce the *%Poor* measure to 2.72 percent for the combined total of NHS and State-owned bridges (FHWA 2024b).

Table 12. Tabular example of StruPlan performance forecast for bridges.

Year	Condition, Good (percent)	Condition, Poor (percent)
2021	28.5	2.93
2022	31.48	2.8
2023	32.84	2.64
2024	34.2	2.59
2025	34.7	2.58
2026	34.98	2.61
2027	35.0	2.65
2028	35.12	2.65
2029	34.98	2.64
2030	34.84	2.65
2031	34.88	2.72
Targets	20	5



© 2020 StruPlan.

Figure 35. Graph. Example of StruPlan performance forecast for bridges for SDDOT.

Cross-Asset Tradeoff Analysis and Results

The South Dakota pilot test of a cross-asset tradeoff analysis was not fully successful due to various issues. The research team found it difficult to compute a consistent benefit-cost performance measure in the PMS. Additionally, the PMS was incapable of generating enough cost-effective projects to maintain current conditions and spend the available budget. Most pavement BCRs were outside the expected range of zero to one and thus either above or below the range of bridge projects. As a result, the TA-MAPO tool was unable to produce meaningful results for resource allocation or demonstrate sensitivity to funding levels within the results (FHWA 2024b).

Diagnosis of the problems observed in the data led the research team to refine the methodology specification to clarify the LCC requirements and expected range of BCRs. The revised description is reflected in chapter 3 and chapter 4 and appendix E.

Another issue that the data illuminated was the difficulty of classifying pavement resurfacing projects as either preservation or rehabilitation. Additionally, the data shed light on the fact that resurfacing made up more than half of the total cost of pavement projects. Resurfacing fits the definition of preservation in that it protects the pavement structure from deterioration and improves the pavement condition. However, resurfacings thicker than 1.5 to 2 inches that impart added structural life to the pavement are generally classified as rehabilitation. In the case of the South Dakota analysis, counting resurfacing projects as preservation resulted in preservation making up 67.58 percent of the pavement investment in the combined program. On the other hand, counting resurfacing projects as rehabilitation resulted in preservation making up only 14.88 percent of the pavement investment.

Another important observation from the data was the importance of quantifying all benefits of pavement work. The PMS primarily relies on a decision tree to mandate reconstruction if a pavement deteriorates to a sufficiently bad condition. The PMS does not attempt to quantify the benefit to road users of this work. This lack of quantification makes implementing any type of cross-asset tradeoff analysis difficult, since the decision rules are specific to pavements and not applicable to bridges or any other asset class. On the other hand, the bridge analysis employs a user cost model to quantify the benefits of bridge reconstruction. Other available tools for cross-asset analysis, such as FHWA's HERS, employ user cost models for both pavements and bridges so that cross-asset tradeoffs can be analyzed (FHWA 2005).

CHAPTER 7. TEXAS VALIDATION STUDY

VALIDATION PROCESS

Texas was the third and final State selected for pilot validation of the NGPPMs and proposed TAMM. Following the selection, the research team conducted a kick-off meeting with TxDOT representatives to introduce team members, review the project, discuss the goals and expectations of the study, and identify any foreseeable challenges. Based on the results of this meeting, the research team developed a preliminary work plan and project schedule to help guide the validation efforts. Revisions to the work plan were then made, as needed, to better accommodate TxDOT's pavement and asset management practices and data. Some key changes to the plan are as follows:

- The RSI analysis could not be conducted using the PMS data because TxDOT's standard PMS analysis module did not generate multiple pavement lifecycle treatment strategies for each segment in the pavement network. Because the AUCR and CAR measures depend on the optimum pavement lifecycle treatment strategy identified through RSI analysis, these measures also could not be validated. Hence, the results obtained from TxDOT's standard PMS analysis configuration were only used to validate the financial performance measures.

- The TAMM validation process analyzed the impact of delaying the suggested treatment by 1 year at a time over the chosen analysis period for each pavement and bridge segment included in the analysis. Although the standard PMS analysis configuration did not support the TAMM validation process, the research team was able to manually generate the data required for analysis by combining the outputs from multiple PMS analysis runs.

Next-Generation Pavement Performance Measures

TxDOT was interested in whether the NGPPMs could help it narrate an account about its pavement management process that could not be communicated with existing pavement condition-based performance measures (cracking, rutting, roughness, OCI, etc.). To accomplish this objective, the research team gathered and analyzed TxDOT's pavement management data and computed four financial NGPPMs (ASI, ASR, ACR, and SLR) (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). The research team then provided suggestions to TxDOT on how the measures could potentially be used to support the existing business processes. Following is a brief description of the steps involved in the validation process:

1. Determine data needed for analysis and review relevant supporting documentation: The research team compiled a list of TxDOT's data needs for computing the performance measures included in the validation effort. Additionally, key TxDOT documents (e.g., 2020 TAMP, pavement treatment definitions) were obtained and reviewed to help identify the parameters involved in calculating the performance measures.

2. Review PMS analysis capabilities: The research team reviewed these capabilities thoroughly while working in close coordination with TxDOT's pavement team. The research team then identified a list of analyses that needed to be conducted with the PMS to enable NGPPM calculation.

3. Conduct PMS analyses: TxDOT's pavement team conducted PMS analysis runs that served as input for calculation of the NGPPMs.

4. Calculate NGPPMs: The research team developed a simple calculation tool to compute financial NGPPMs. This tool used the PMS analysis results from step 3 for the calculations.

Proposed Transportation Asset Management Methodology

As with the ITD and SDDOT validation efforts, the research team requested detailed pavement and bridge data from TxDOT and then entered into the TA-MAPO tool to analyze tradeoffs among costs and conditions across asset classes and subnetworks. A separate spreadsheet model was used to accumulate PMS data and calculate the performance measures from multiple analytical runs. Additionally, the StruPlan spreadsheet program was used to generate bridge work candidates, which were then combined with pavement work candidates to form the investment candidate file used in the TA-MAPO tool (Thompson 2021; Ram et al. 2023).

DATA AND INFORMATION GATHERING

This section presents details on the data and information-gathering efforts for the performance measure validation process.

Data for Next Generation Pavement Performance Measure Validations

Initial Data Request

The research team held several web meetings with the FHWA panel and the TxDOT staff to identify the information necessary for the validation process (appendix D). As a result of these meetings, the following datasets and documentation were initially requested and obtained from TxDOT:

- PMS treatments: TxDOT provided the documentation on their pavement treatment types and unit costs and the decision trees they used for treatment selection.

- PMS analysis output files: TxDOT provided a sample PMS analysis output file for the research team to review as part of the initial data request. Key information included in the output file were as follows:

    - Annual budget for analysis run.
    - Segment ID and location for linking to the condition summary and data collection tables.
    - Treatment recommendations for all segments.
    - Treatment selections within the budget.
    - Treatment costs for all recommended and selected treatments.
    - Conditions for all available distresses and indices at the start and end of each year.

It was decided that data from two districts would be used for the performance measure validation process because TxDOT's pavement network was large. After evaluating the adequacy of the sample data provided to calculate the financial measures, PMS outputs for the Houston and Brownwood districts were requested. These districts were selected because they had good mixes of pavement types (flexible and rigid) and roadway settings (urban and rural).

A summary of the input parameters and budget levels selected for use in the validation analysis is as follows:

- Analysis period: 20 years.
- Discount rate: No discount rate or inflation rate was considered (real discount rate = 0 percent).
- Annual budget level: The current budgets used during the scenario runs were as follows:
    - Houston District: $100 million per year.
    - Brownwood District: $29 million per year.
- Analysis network: Houston District:
    - Number of segments: 3,306.
    - Total lane-miles: 11,546.
    - Pavement type distribution: CRC (54 percent), asphalt concrete (AC) (43 percent), jointed plain concrete (JPC) (3 percent).
    - Roadway setting classification: Urban.
- Analysis network: Brownwood District:
    - Number of segments: 1,906.
    - Total lane-miles: 5,976.
    - Pavement type distribution: AC (100 percent).
    - Roadway setting classification: Rural.

Additional Data Request

Two additional budget scenario runs for each district were requested to better characterize the pavement need parameter. The additional budget scenario runs evaluated were 15 percent and 30 percent below the budget level at the time.

Data for Transportation Asset Management Methodology Validation

Pavement Data

Since TxDOT's PMS was not configured to generate strategies based on delaying treatments by 1 year at a time, the project team used the results of the do-nothing scenario run to generate inputs in a format that was compatible with the TA-MAPO tool. The do-nothing scenario provided details on treatments that would be triggered over the analysis period if funding were available. This information, in conjunction with TxDOT's treatment decision trees, was used to develop a simplified process to generate the inputs required for the TA-MAPO tool. Although the TA-MAPO tool conducted the analysis over a 10-year period, the PMS analysis was conducted for a 20-year analysis period to evaluate the long-term impact (in terms of change in LCC) of delaying treatments.

Bridge Data

At the time of the validation study, TxDOT was in the early stages of implementing AASHTOWare BrM (AASHTO 2023). The agency did not yet have full statewide coverage of element data for non-NHS bridges and had not developed element-level deterioration or cost models suitable for LCCA. TxDOT staff provided a complete file containing the same statewide data that were submitted to FHWA in 2021 for the NBI (FHWA 2023). The research team pared this dataset down to just the Houston and Brownwood districts to make it compatible with the pavement analysis. The final dataset contained 2,216 bridges, all of which were State-owned bridges on the NHS.

As with the other pilot studies, StruPlan was employed to generate investment candidates with the necessary performance measures for prioritization and outcome forecasting. The deterioration model was derived from the NBIAS for climate zone 6 (damp warm) (Thompson n.d.a).[25] Because TxDOT did not provide cost data for the analysis, the StruPlan default cost models, which are based on Kentucky bid tabulations, were used.

VALIDATION ANALYSES AND RESULTS

This section presents results of the NGPPM and TAMM validation efforts.

Financial Performance Measures

The NGPPM validation efforts were focused on the following four financial measures:

- ASI: The ratio of planned investment to the budget needed to maintain the assets at the desired condition (Proctor, Varma, and Varnedoe 2012). The key parameter used in calculating the ASI measure is pavement need, which is the budget needed to maintain the network at the desired SOGR.

- ASR: The ratio of the investments to the depreciation under zero investment for a chosen fiscal period (Ram et al. 2023). The annual depreciation under zero investment was calculated by aggregating the annual depreciation calculation (discussed in the next section) and the pavement investment need. The pavement value depreciation used in the

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[25] FHWA. 1999–2024. *NBIAS* investment analysis tool (software).

ASR calculation is based on the condition score (CS), an overall index that captures distress and ride.

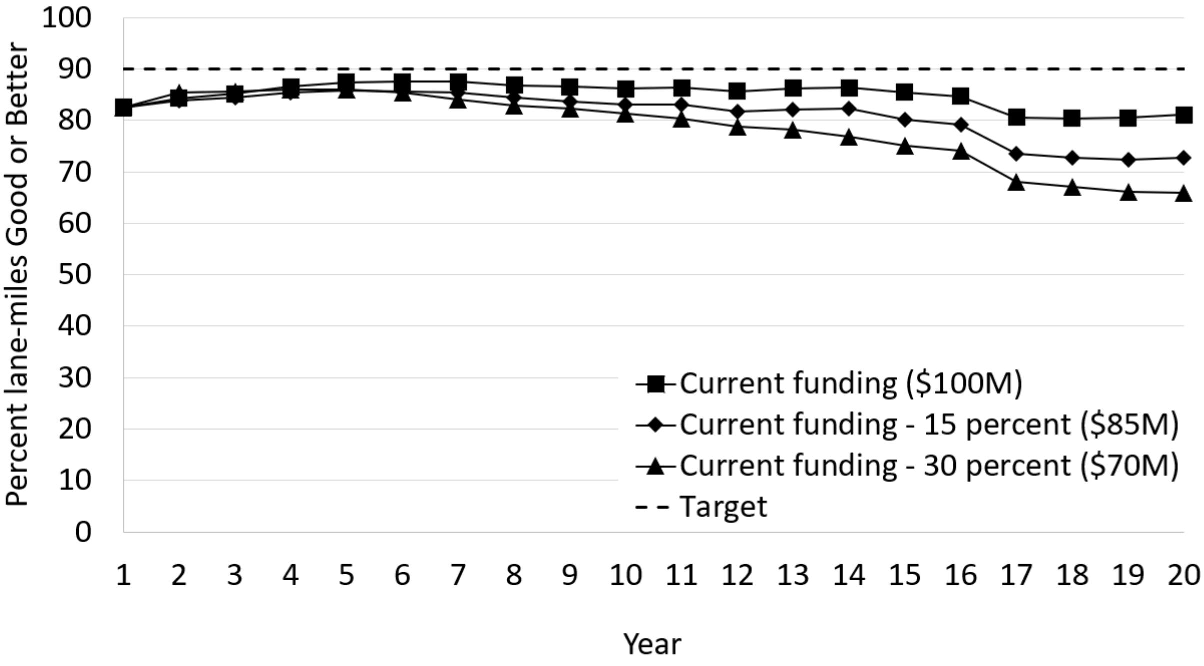
- ACR: The ratio of the depreciated replacement cost to the current replacement cost (Ram et al. 2023).
- SLR: The ratio of the unfunded PMS treatments to the replacement cost of the pavement network (Ram et al. 2023). The unfunded treatment need/backlog is a direct output from TxDOT's PMS analysis runs.

Data Preprocessing

The primary task during the financial measure calculation process was the identification of the necessary data elements from the PMS data output files (appendix D). Once the key data elements were identified, the research team then analyzed several parameters used in computing the financial measures. This section summarizes the parameters that were calculated.

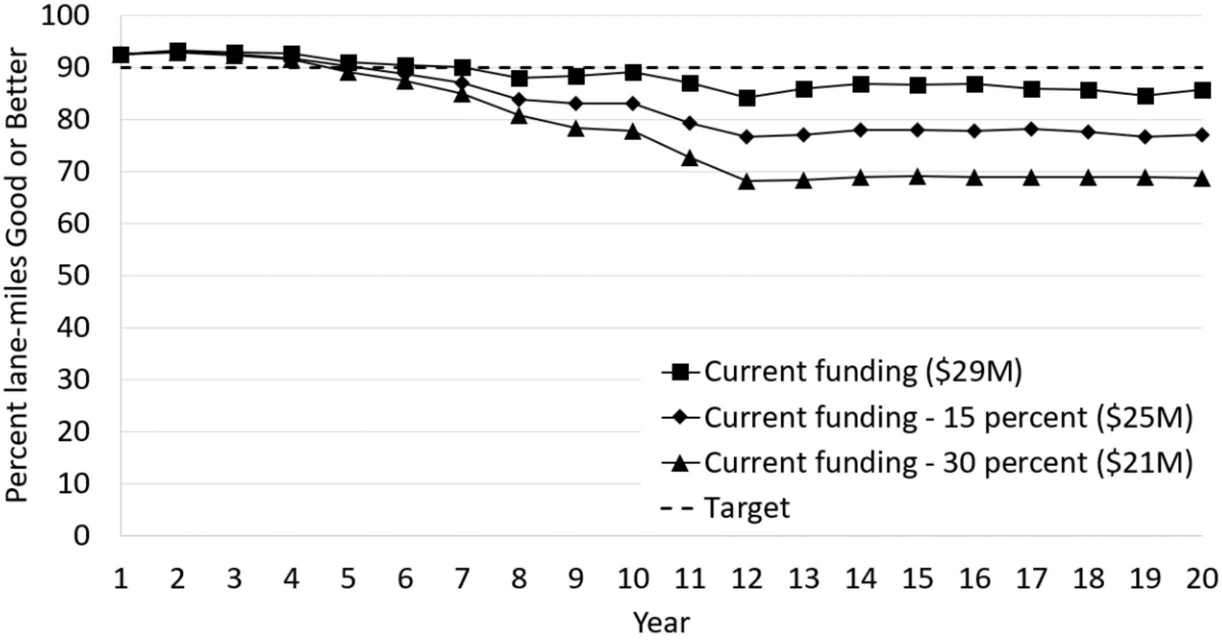
Percent Lane-Miles in Good or Better *Condition*

The term *Good or Better* refers to a CS of 70 or higher. TxDOT's statewide pavement condition goal was 90 percent of the lane-miles in *Good or Better* condition. The percent of lane-miles in *Good or Better* condition over the 20-year analysis period for each funding scenario evaluated for the Houston and Brownwood districts are shown in figure 36 and figure 37, respectively.



Source: FHWA.

Figure 36. Graph. Percent lane-miles in *Good or Better* condition in Houston District.



Source: FHWA.

Figure 37. Graph. Percent lane-miles in *Good or Better* condition in Brownwood District.

Observations of the trends in figure 36 and figure 37 are as follows:

- Houston District: The percent of lane-miles in *Good or Better* condition exhibits a slightly increasing trend in the first 6 years for all the funding scenarios. After the initial increase, the trends for the reduced funding levels start declining at a steady rate until year 16. A sharp decline is observed between year 16 and year 17 for all the funding scenarios. At the end of the 20-year analysis period, a 30-percent reduction in the budget level results in a 19-percent decline in the fraction of lane-miles in *Good or Better* condition.

- Brownwood District: The fraction of lane-miles in *Good of Better* condition meets TxDOT's performance goal for all three budget scenarios for the first 5 years. After year 5, the impact of reducing the funding level becomes apparent as the gap between the trendlines begins to widen over time. After 20 years, a 30-percent reduction in the budget level results in a 20-percent decline in the fraction of lane-miles in *Good or Better* condition.

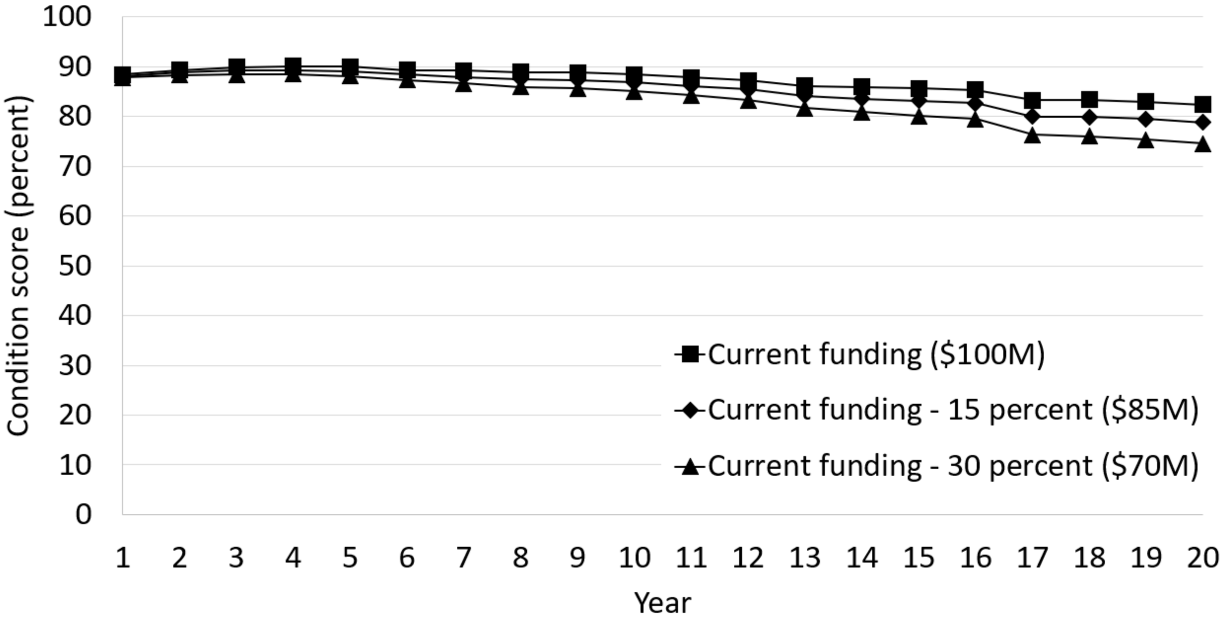
Pavement Condition Trends

The research team analyzed pavement condition trends by plotting the annual network-level weighted average conditions over the 20-year analysis period. The pavement CSs for the following annual budget scenarios were evaluated:

- Houston District: $100 million (current funding), $85 million (15 percent below current budget), and $70 million (30 percent below current budget).

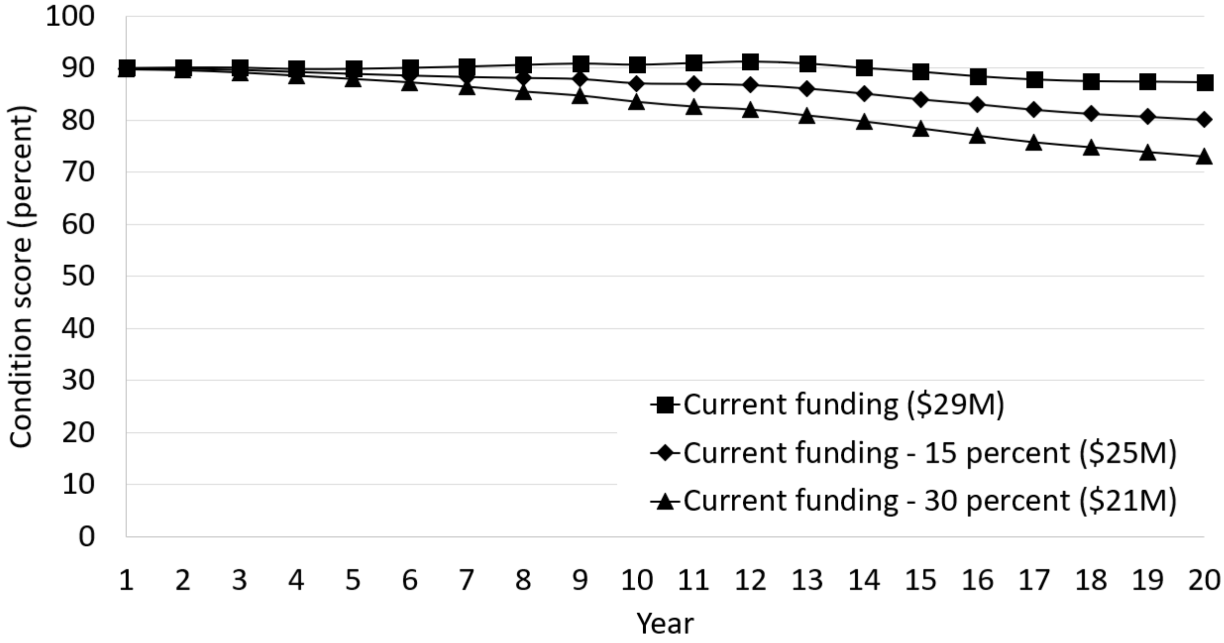
- Brownwood District: $29 million (current funding), $25 million (15 percent below current budget), and $21 million (30 percent below current budget).

The results are presented in figure 38 and figure 39, respectively. At the current funding level for Houston District, the weighted average CS (weighted by segment lane-miles) after 20 years is approximately 82. For Brownwood District, the CS remains around 90 throughout the analysis period. A 30-percent budget reduction results in a 10-percent reduction in CS for Houston District and a 16-percent reduction in CS for Brownwood District.



Source: FHWA.

Figure 38. Graph. Houston District pavement condition trends.



Source: FHWA.

Figure 39. Graph. Brownwood District pavement condition trends.

The results suggested that the pavement network in Brownwood District was more sensitive to budget cuts than the network in Houston District.

Project-Level and Network-Level Parameters

The research team calculated parameters for each year in the analysis period for each pavement segment and for the entire pavement network for all the PMS runs for each district. Some of these parameters are as follows:

- Replacement cost: Calculated with the unit cost of heavy rehabilitation for the entire pavement segment.

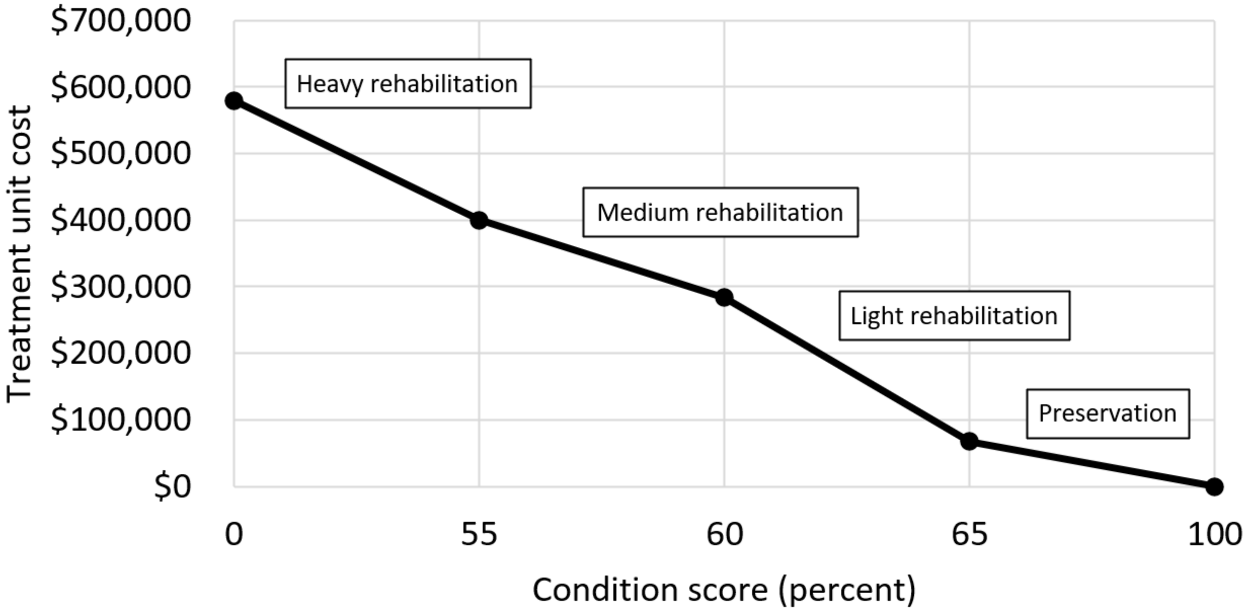
- Depreciation: Developed by the research team, the asset value depreciation calculation model follows a simple piecewise linear depreciation approach, as TxDOT's PMS does not calculate depreciation. Pavement value depreciation for a segment is tied to the projected pavement condition at each year in the analysis (determined by the performance models programmed in the PMS), pavement type (flexible or rigid), and traffic level (less than 1,450 annual average daily traffic (AADT) per lane, between 1,450 and 5,000 AADT per lane, greater than 5,000 AADT per lane). The depreciation in each pavement segment is approximated to be the cost of treatment(s) required to restore the condition of the pavement close to an as-built condition. Figure 40 illustrates the depreciation calculations for a CS value of 30 for flexible pavements subjected to traffic levels of greater than 5,000 ADT per lane. The depreciation models for the rest of the pavement types and traffic levels are shown in figure 41 through figure 45.

- Depreciated replacement cost: Calculated as the difference between the replacement cost and the accumulated depreciation.

Texas treatment type: Mapped to the FHWA work types. Texas had already mapped its pavement and bridge treatments to the FHWA work types during the development of its TAMP (TxDOT 2020).

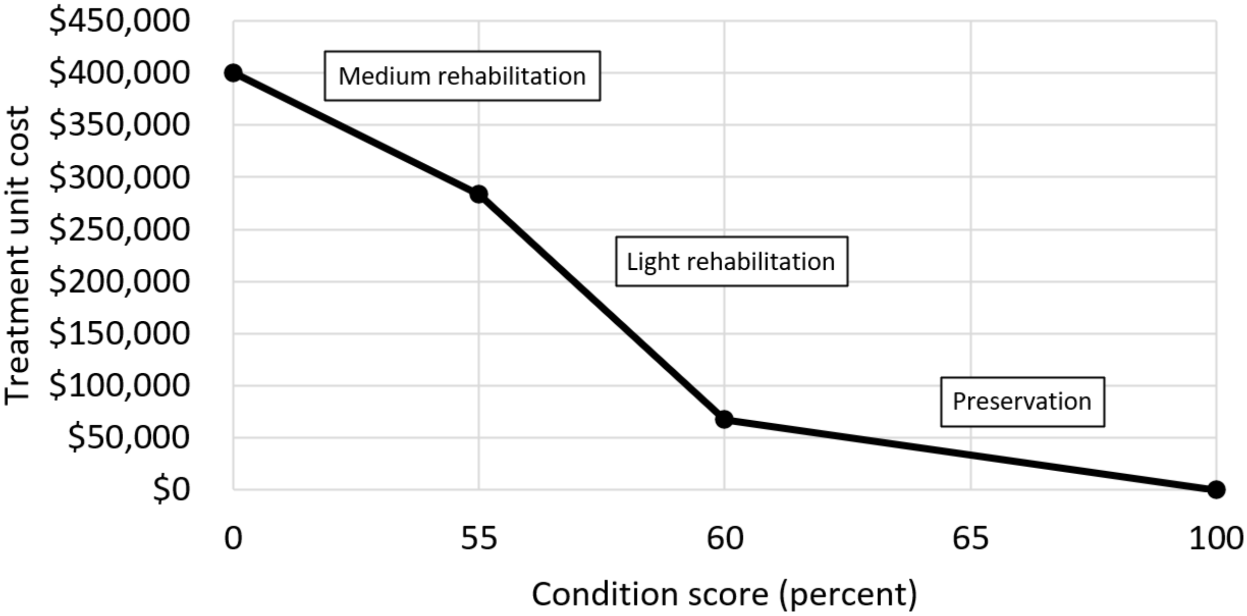
- Table 66 in appendix D summarizes the treatment mapping from Texas treatments to FHWA work types.

- Pavement need: This parameter is the annual funding level required to meet the desired SOGR. Estimating this parameter is a crucial step in calculating the ASI and ASR financial measures. TxDOT's desired SOGR is to maintain 90 percent of lane-miles in *Good or Better* condition. If the current budget level was able to achieve this desired SOGR, then the need was assumed to be the same as the budget level. If the current budget was unable to meet the desired SOGR, then the results from each of the three budget-constrained analysis runs were used to develop a regression model that helped to establish the pavement need for each year over the 20-year analysis period. For the reduced budget scenarios, the calculated need was recalibrated based on the fraction of lane-miles in *Good or Better* condition in each year over the analysis period.



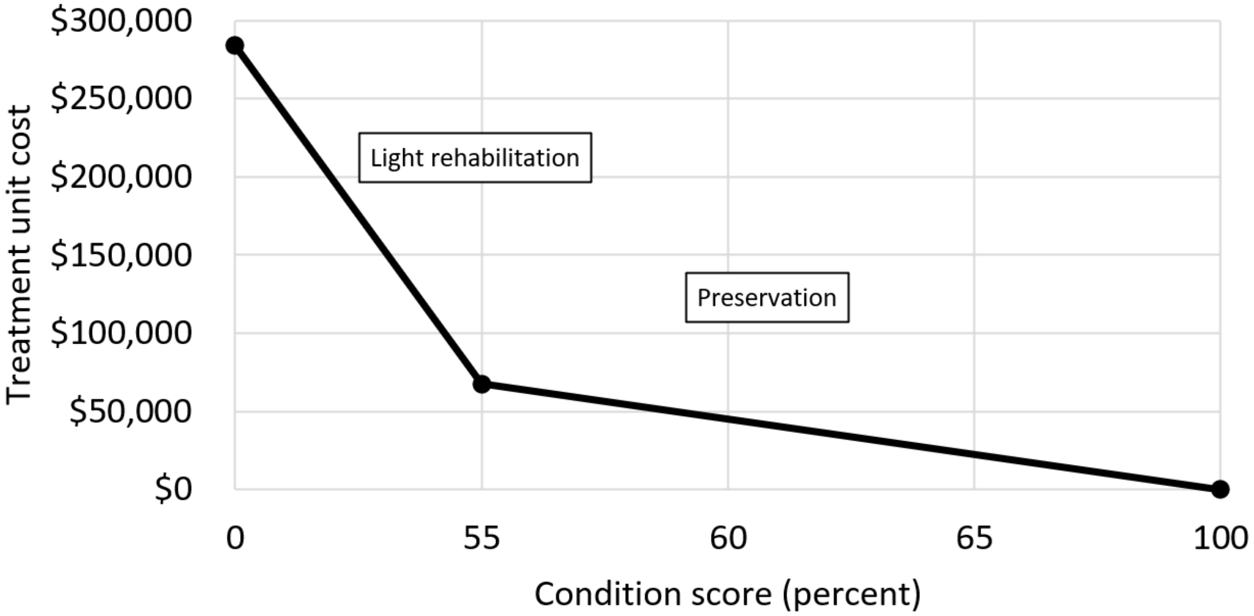
Source: FHWA.

Figure 40. Graph. Depreciation calculation model for flexible pavements with traffic levels greater than 5,000 ADT per lane.



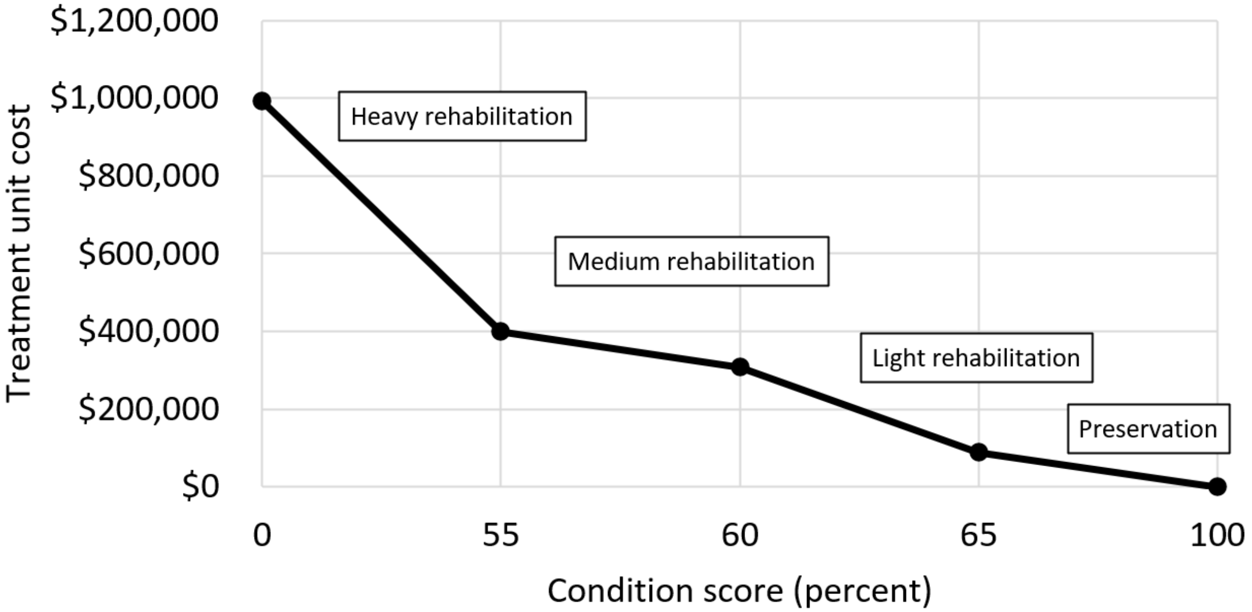
Source: FHWA.

Figure 41. Graph. Depreciation calculation model for flexible pavements with traffic levels between 1,450 and 5,000 ADT per lane.



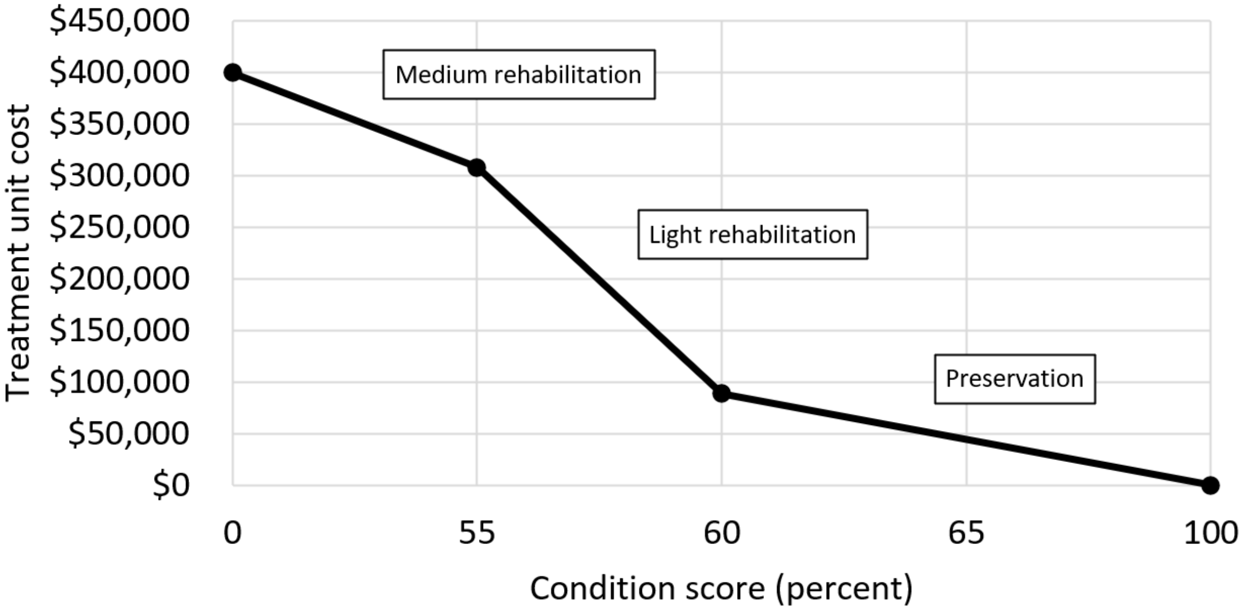
Source: FHWA.

Figure 42. Graph. Depreciation calculation model for flexible pavements with traffic levels less than 1,450 ADT per lane.



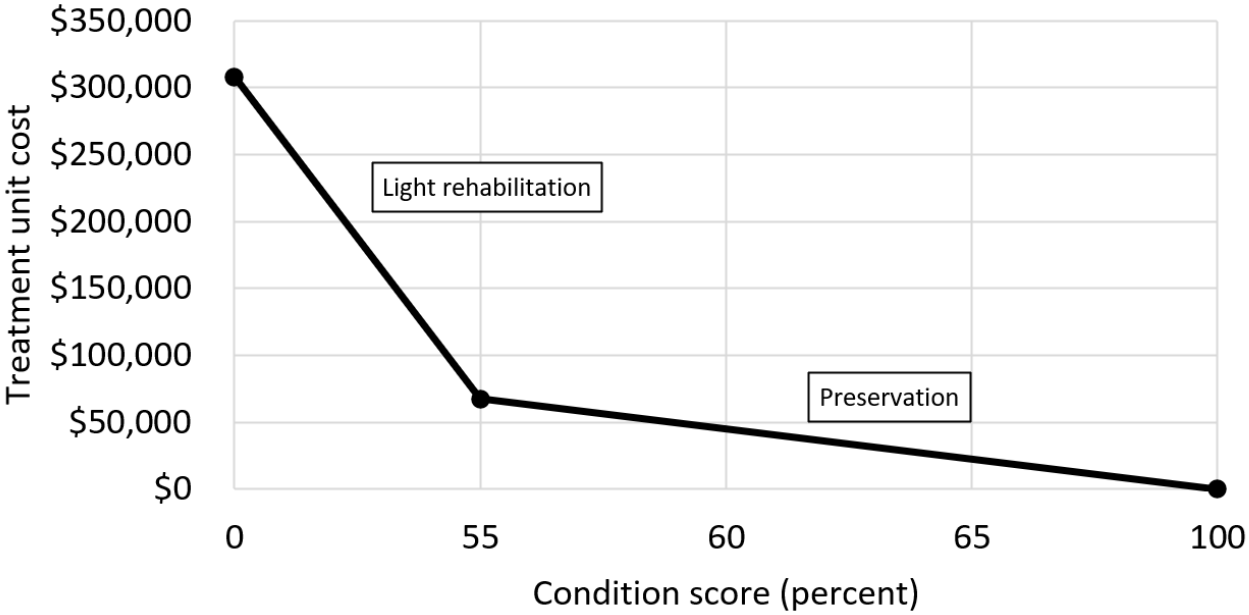
Source: FHWA.

Figure 43. Graph. Depreciation calculation model for rigid pavements with traffic levels greater than 5,000 ADT per lane.



Source: FHWA.

Figure 44. Graph. Depreciation calculation model for rigid pavements with traffic levels between 1,450 and 5,000 ADT per lane.



Source: FHWA.

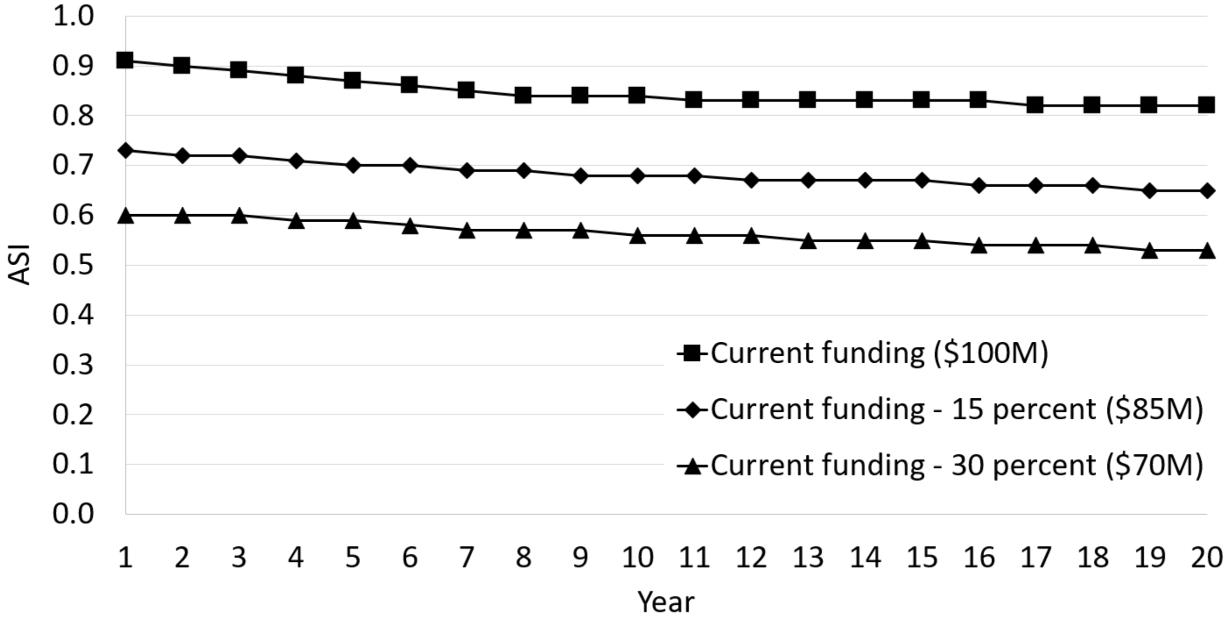
Figure 45. Graph. Depreciation calculation model for rigid pavements with traffic levels less than 1,450 ADT per lane.

Financial Performance Measure Results

As part of the NGPPM validation, the research team calculated four financial measures using the pavement data from the PMS runs. For Houston District, annual budget levels of $100 million, $85 million, and $70 million were used. For Brownwood District, annual budget levels of $29 million, $25 million, and $21 million were used.

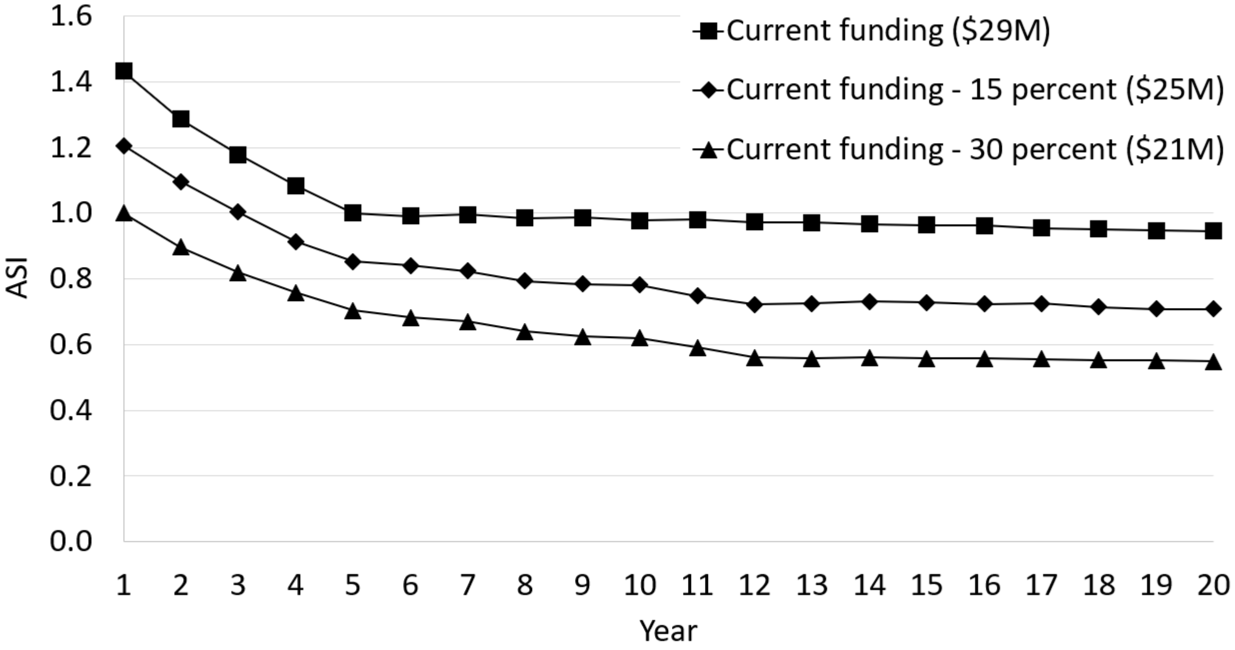
Asset Sustainability Index

Figure 46 and figure 47 illustrate the ASI trends over the 20-year analysis period for the Houston and Brownwood districts, respectively.



Source: FHWA.

Figure 46. Graph. Network-level ASI trends for Houston District over the 20-year analysis period.



Source: FHWA.

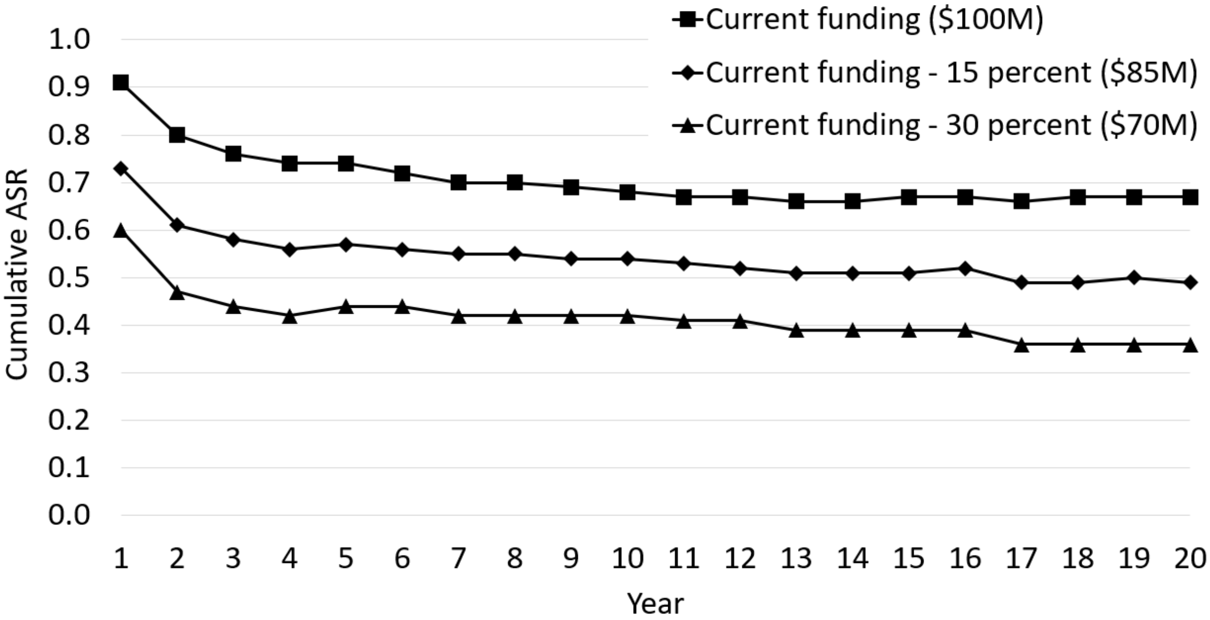
Figure 47. Graph. Network-level ASI trends for Brownwood District over the 20-year analysis period.

The key takeaways from these figures are as follows:

- Houston District:
  - The current $100 million annual funding level results in ASI of less than one throughout the analysis period. However, the values are generally above 0.8, which indicates that most needs are being addressed.
  - Funding levels reduced by 15 percent and 30 percent result in ASI of 0.6 and 0.5 at the end of the analysis period, respectively. These results reflect funding levels that are not adequate to address the needs.
- Brownwood District:
  - The current $29 million annual funding level results in ASI of greater than 1 over the first 4 years. Between year 5 and year 20, the ASI values are generally above 0.95, which suggests that the current annual funding almost meets the pavement need.
  - The reduced funding levels result in unsustainable ASI in the long-term, as the ASI drops to 0.71 and 0.55 at year 20, when the funding levels are reduced by 15 percent and 30 percent, respectively.

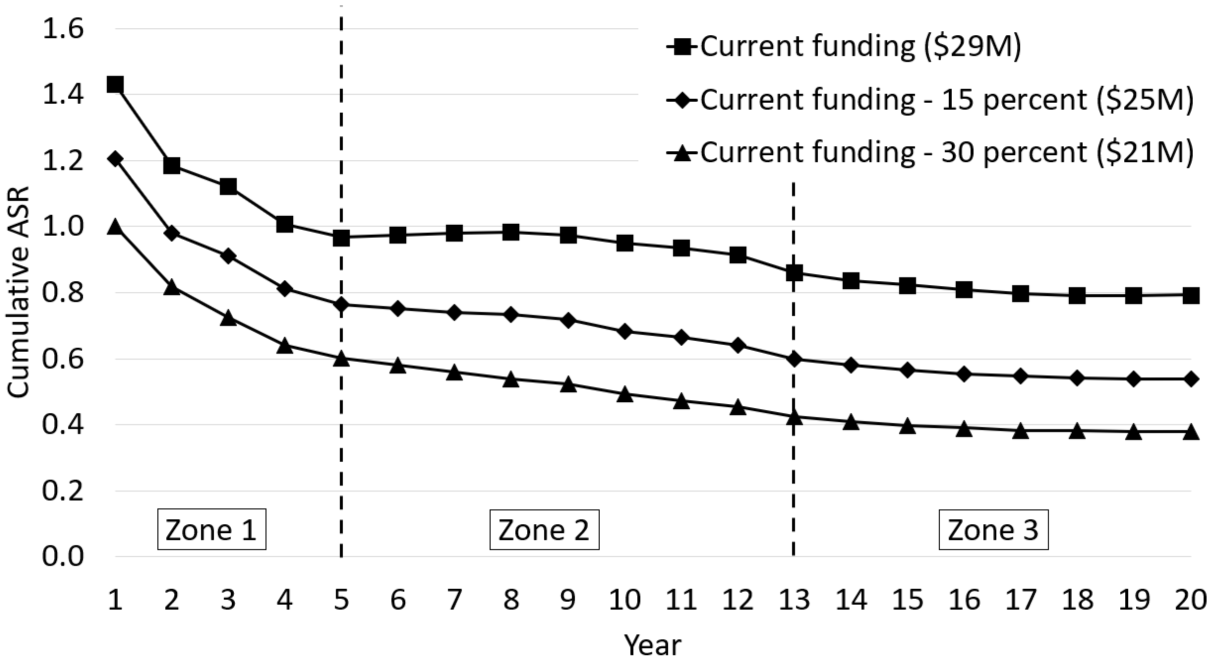
Asset Sustainability Ratio

Figure 48 and figure 49 illustrate the cumulative ASR trends over the 20-year analysis period for the Houston and Brownwood districts, respectively.



Source: FHWA.

Figure 48. Graph. Network-level ASR trends for Houston District over the 20-year analysis period.



Source: FHWA.

Figure 49. Graph. Network-level ASR trends for Brownwood District over the 20-year analysis period.

The key takeaways from these figures are as follows:

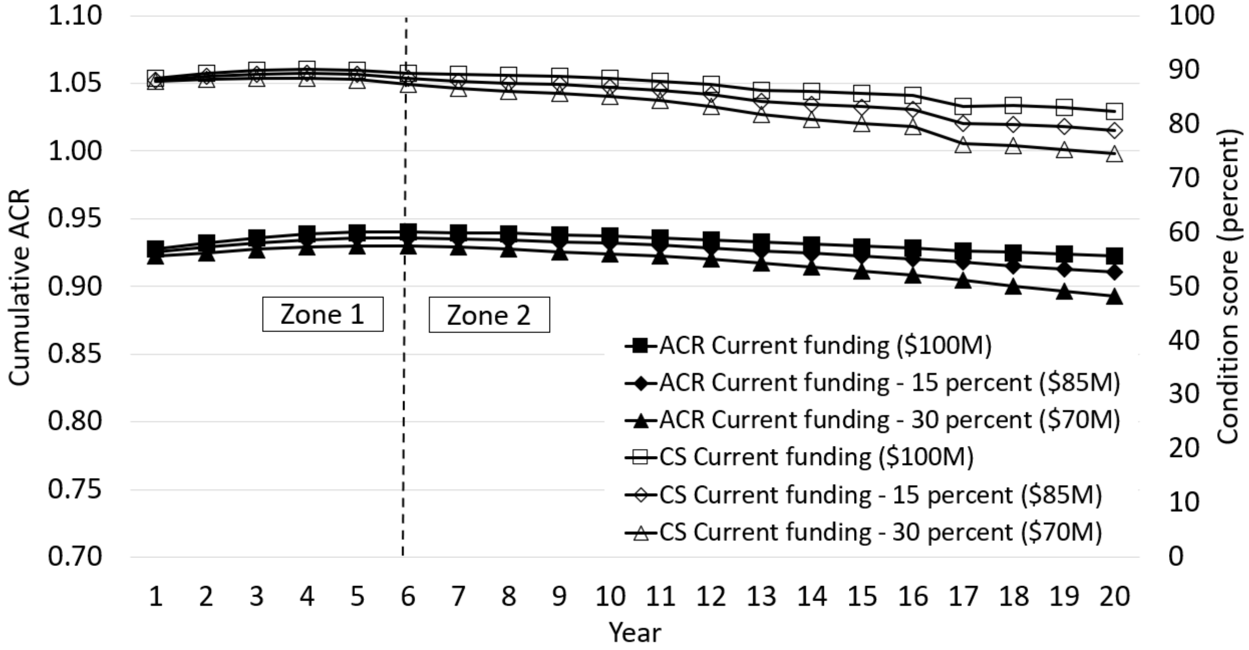
- Houston District:
    - The ASR trends decline for each of the three budget scenarios evaluated over the first 4 years; subsequently, the values appear to achieve a steady-state condition. Since most of the decline occurs in the first 4 years, additional investments in major treatments (major rehabilitation and reconstruction) are needed to offset the depreciation incurred.
    - The ASR stays near 0.7 for the current funding level at the end of the analysis period. A slight increase in ASR is observed in year 13 and year 17. This increase corresponds to an increase in rigid pavement rehabilitation treatments.
    - The reduced funding levels result in significantly lower ASR (<0.5) at the end of the analysis period in comparison to the current funding level.
- Brownwood District:
    - The ASR trends are categorized into zone 1 (year 1 through year 5), zone 2 (year 6 through year 13), and zone 3 (year 14 through year 20). A higher rate of ASR decline is observed in zone 1 for all the funding scenarios evaluated. In zone 2, the ASR declines at a much slower rate; in zone 3, the ASR trend appears to reach a steady state. This trend indicates that additional investments in heavier treatments are needed to effectively offset asset value depreciation toward the end of zone 1.

- The current annual budget can achieve an ASR of almost 80 percent at the end of the analysis period, which indicates that the current annual funding is generally effective in offsetting asset value depreciation.

- The reduced funding levels will result in significantly lower ASR (<0.54) at the end of the analysis period. These results clearly indicate these funding levels are not sustainable in the long term.

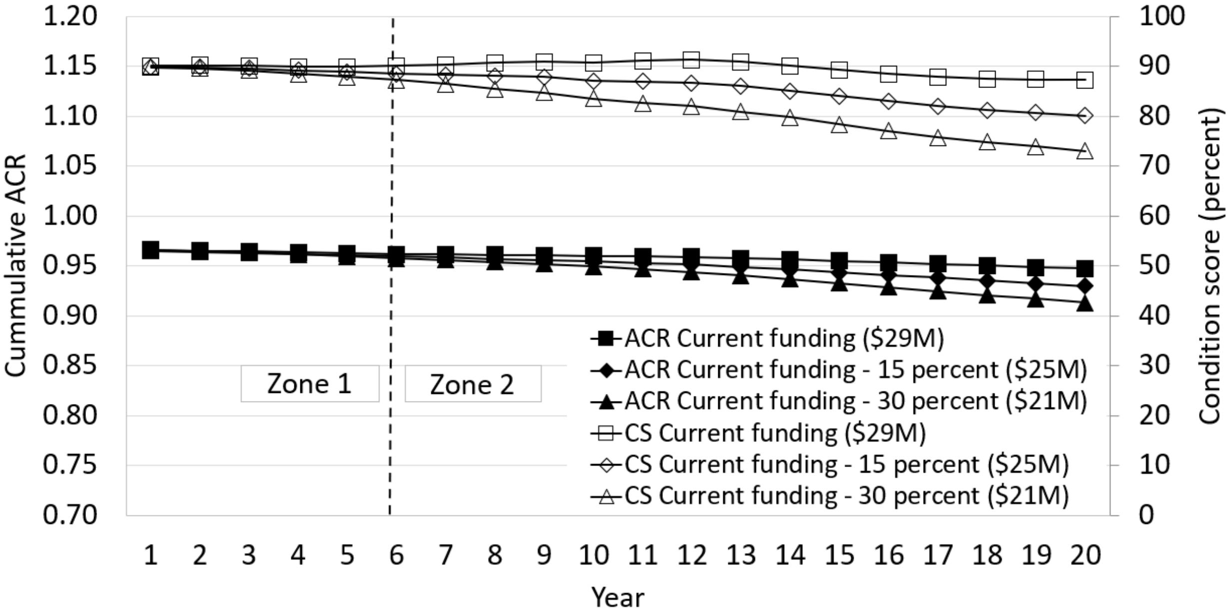
Asset Consumption Ratio

Figure 50 and figure 51 illustrate ACR trends over the 20-year analysis period for the Houston and Brownwood districts, respectively.



Source: FHWA.

Figure 50. Graph. Network-level ACR trends for Houston District over the 20-year analysis period.



Source: FHWA.

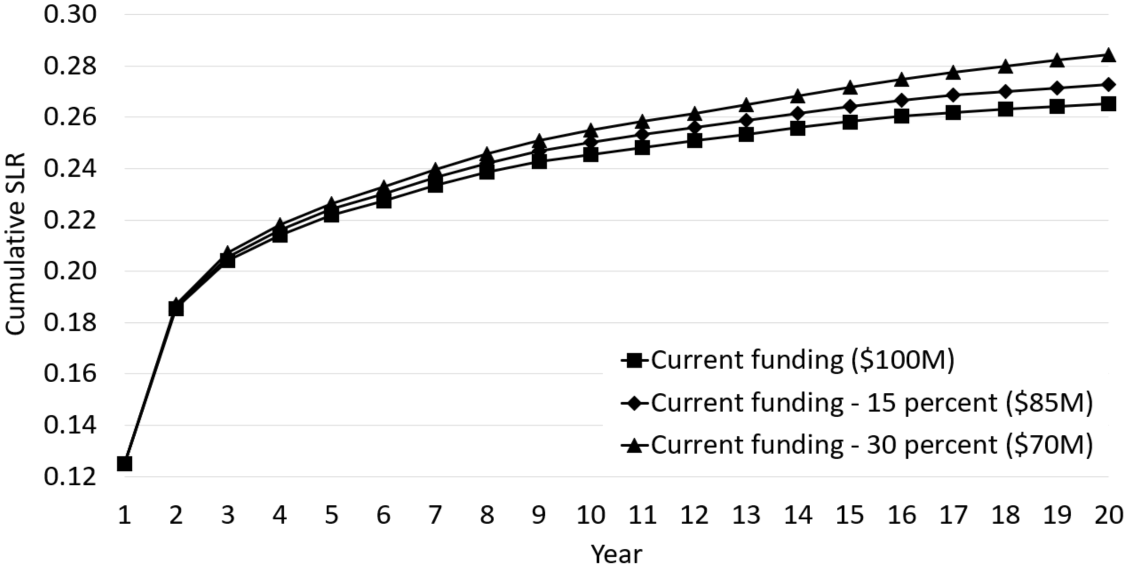
Figure 51. Graph. Network-level ACR trends for Brownwood District over the 20-year analysis period.

The key takeaways from these figures are as follows:

- Houston District:
  - ACR trends resemble the pavement condition trends closely. For the current funding scenario, the ACR values are at or above the 0.9 mark throughout the analysis period. The high value is primarily due to the way the performance measure is calculated; the large denominator value (replacement value of the pavement network) results in the measure being less sensitive to depreciation and investments than some of the other measures.
  - Figure 50 illustrates the way ACR trends can be categorized into two zones. In zone 1, the ACR increases until year 6. The reason for this increase is the rigid pavement rehabilitation treatments triggered by the PMS within the first 5 years of the analysis. In zone 2, ACR trends exhibit a slightly declining trend after year 6, and the gaps between different funding scenarios start increasing gradually.
- Brownwood District:
  - Figure 51 illustrates the way ACR trends can be categorized into two zones. The ACR trends remain fairly constant in zone 1; in zone 2, the gaps between different funding scenarios start to gradually increase.
  - The ACR trends resemble the pavement condition trends. Even at the end of the 20-year analysis period, the ACR for all three budget levels are fairly high, which indicates that this measure is not particularly useful in making treatment strategy decisions.

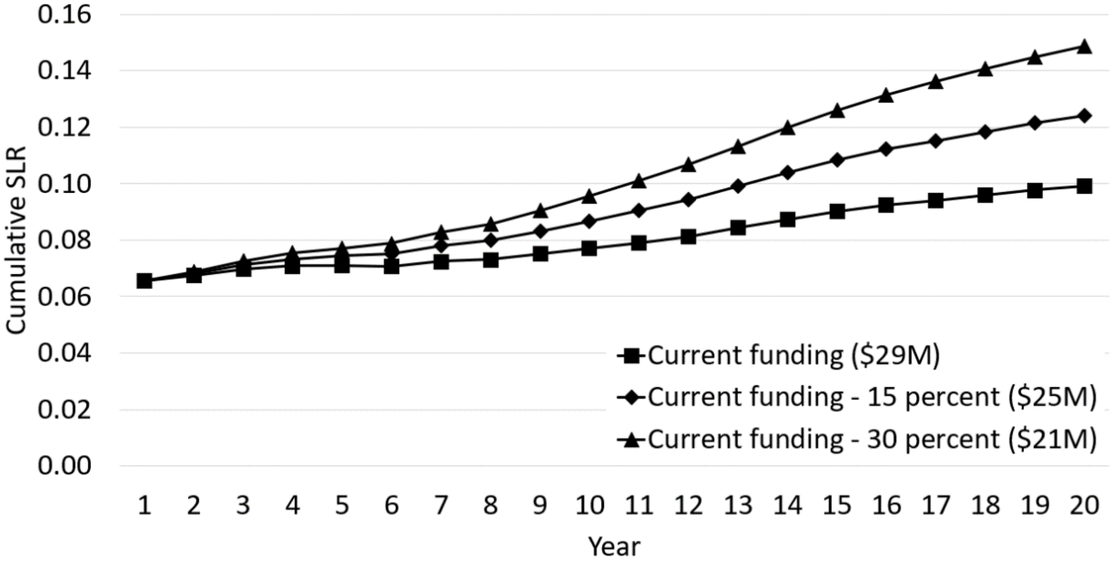
Stewardship Liability Ratio

The SLR is an indicator of the proportion of unfunded pavement management treatment recommendations to the replacement value of the pavement network. While it is not practical or realistic to expect an agency to eliminate its treatment backlog altogether, it is important to keep the backlog growth in check. Figure 52 and figure 53 illustrate the SLR trends over the 20-year analysis period for the Houston and Brownwood districts, respectively. Table 13 and table 14 summarize the SLR and backlog values at the beginning and end of the analysis period for each district.



Source: FHWA.

Figure 52. Graph. Network-level SLR trends for Houston District over the 20-year analysis period.



Source: FHWA.

Figure 53. Graph. Network-level SLR trends for Brownwood District over the 20-year analysis period.

Table 13. Year 2 versus year 20 SLR and backlog values for Houston District.

Funding Scenario	SLR at Year 2	SLR at Year 20	Change (percent)	Backlog at Year 2 (billions of dollars)	Backlog at Year 20 (billions of dollars)	Percentage Change
Current funding ($100 million)	0.19	0.27	42	2.3	2.7	17
Current funding −15% ($85 million)	0.19	0.27	42	2.3	2.8	22
Current funding −30% ($70 million)	0.19	0.28	47	2.3	3.0	30

Table 14. Year 2 versus year 20 SLR and backlog values for Brownwood District.

Funding Scenario	SLR at Year 2	SLR at Year 20	Change (percent)	Backlog at Year 2 (billions of dollars)	Backlog at Year 20 (billions of dollars)	Percentage Change
Current funding ($29 million)	0.07	0.10	43	2.3	4.4	91
Current funding −15% ($25 million)	0.07	0.12	57	2.3	6.1	165
Current funding −30% ($21 million)	0.07	0.15	114	2.3	7.8	239

The key takeaways from these figures and tables are as follows:

- Houston District:
  - The SLR gradually increases over the analysis period for each of the three funding levels evaluated. At the end of the analysis period, each of the three funding levels results in similar SLRs.
  - The backlog values come fairly close for each funding level investigated at the end of the analysis period, much like the SLR values. The current funding results in a backlog of $2.7 billion at year 20. In comparison, the backlog at year 20 for a 30-percent reduction in funding level is $3 billion.

- Brownwood District:
    - The SLR trends are similar for each funding level over the first 6 years. However, after year 6, the SLR increases, corresponding to a reduction in funding. Unlike Houston District, Brownwood District's SLR values for each funding level are significantly different at the end of the analysis period. The current funding scenario has a 43-percent increase in SLR at year 20 compared to initial conditions; a 30-percent reduction in funding results in a 114-percent increase in SLR at year 20 compared to initial conditions.
    - The backlog values are significantly different for each funding scenario investigated at the end of the analysis period, similar to the SLR values. The current funding level results in a 91-percent increase in backlog values at year 20 compared to initial conditions, whereas a 30 percent reduction in funding results in a 239-percent increase in SLR at year 20 compared to initial conditions.

The results of this analysis clearly indicated that the pavement network in Brownwood District was more sensitive to budget cuts than the pavement network in Houston District.

Proposed Transportation Asset Management Methodology

Pavement Data Preprocessing

The TAMM validation was performed using the TA-MAPO tool. The TA-MAPO tool requires the pavement data to conform to a specific format, as specified in a pavement candidate file. Therefore, the primary task during the TAMM validation process was the identification of the necessary pavement data elements from the PMS data output file to map to the pavement candidate file (illustrated in table 65 in appendix D). Once the key data elements were identified and mapped, the research team was able to generate the pavement candidate file for the analysis. Following is a summary of the key considerations and assumptions the research team made during the analysis (FHWA 2024b):

- The LCC was calculated with a 20-year analysis period even though the TA-MAPO tool only analyzed 10 years of treatment suggestions.
- The agency benefit was based on reducing the LCCs of managing the pavement network. Agency savings was calculated as the difference in LCCs between strategies where treatment is deferred by 1 year.
- Pavement user cost was assessed with a value of zero, as there was no suitable approach to calculate user costs at the network level using TxDOT's PMS.
- Safety and mobility performance outcomes were assigned a default value of 100, as they were not direct outputs from the PMS.
- Maintenance cost savings were built into the LCC calculations, so they were not provided as a separate output.

- The TA-MAPO tool documented pavement condition in terms of *%Good* and *%Poor*. To obtain these parameters, pavement condition values were converted to Good (CS ≥ 70), Fair (50 ≤ CS ≤ 70), and Poor (CS < 50). The assumptions the research team considered to convert the Good/Fair/Poor pavement condition ratings to *%Good* and *%Poor* is described in appendix E (FHWA 2024b; Office of the Federal Register 2017).

Bridge Data Preprocessing

Bridge data were prepared in StruPlan using a process similar to the process used for Idaho and South Dakota. Since bridge and element data were provided in the NBI delimited text format, minimal changes were required to adapt the dataset to StruPlan. TxDOT was in the process of phasing out its agency-defined elements, so only NBI elements were considered (FHWA 2023). All 2,216 bridges were State-owned structures on the NHS, located in the Houston and Brownwood districts.

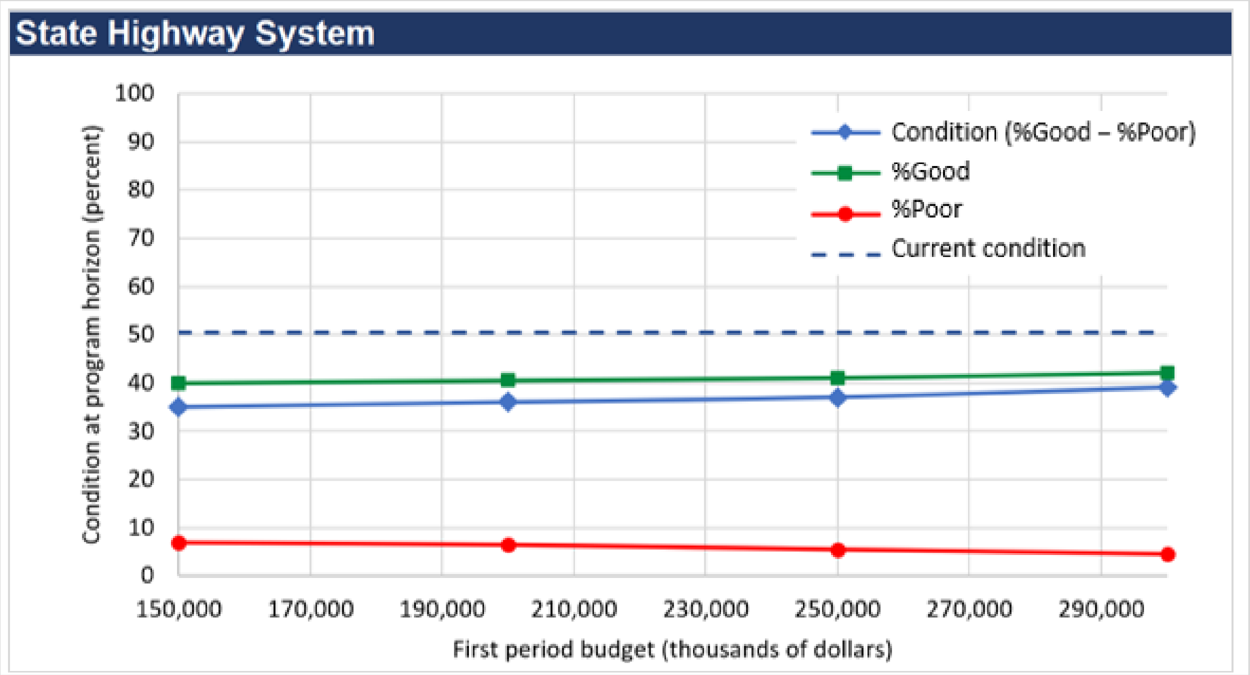
The cross-asset prioritization measure, based on element-level LCCA, used a real discount rate of 2 percent. The analysis was conducted over 75 years, with an additional perpetuity model to pick up any residual costs beyond 75 years. Bridges having a deficient roadway width and/or operating rating were identified, and corresponding user costs were calculated using the methodology of the AASHTO Red Book (AASHTO 2010). Since all the bridges were on the NHS, such deficiencies were relatively few and had relatively little impact compared to the other pilot studies.

An anticipated funding level of $100 million had been identified for the two TxDOT districts, which was insufficient to maintain current conditions. The percent in Good condition (by deck area) declined from 44 percent to 32 percent, and the percent in Poor condition increased from 1 percent to 3 percent at this funding level. Both the inflation rate and the real growth rate were set at 3 percent per year, so there was no loss of buying power due to inflation.

Cross-Asset Tradeoff Analysis and Results

The pavement and bridge data were prepared separately in their respective spreadsheet tools and then combined into the investment candidate file in the TA-MAPO tool. No problems were encountered in this step. However, the investment candidates did manifest some of the same problems encountered in the other pilot studies, particularly that there were not enough pavement projects with a BCR greater than zero to maintain current conditions or spend the available funding. This limitation was not a problem with the identified projects but was an issue in the sense that the PMS did not use LCCs as project justifications. In the bridge management analysis, the deterioration and cost models were not Texas-specific, so their accuracy could not be adequately assessed for use in Texas.

In spite of these issues, the TA-MAPO tool did have enough information to demonstrate the desired tradeoff behavior. For example, the weights assigned to condition, safety, and mobility affected forecast outcomes in the expected ways in a sensitivity analysis. Adding weight to safety caused an increase in the priority of bridge widening projects, which reduced road user costs and improved safety performance. Changes in the total funding provided to the model had the expected effects on performance outcomes—more funding produced better conditions (figure 54) (FHWA 2024b).



Source: FHWA.

Figure 54. Graph. Effects of annual funding levels on network conditions for Houston and Brownwood Districts combined.

Because of the inability of both the PMS and BMS to perform LCCA, the data available for the TA-MAPO were less realistic than were the other pilots' data. They provided the desired validation of the TA-MAPO tool, but further implementation of pavement and bridge management within TxDOT would be required to assess the usefulness of a cross-asset methodology for decisionmaking.

CHAPTER 8. FEDERAL VALIDATION STUDY

VALIDATION PROCESS

In addition to validating the NGPPMs at the State level, this study sought to validate the measures at the Federal level using data from FHWA's HPMS database and modeling and analytics from the HERS software (FHWA 2016, 2005). The validation efforts were focused on three lifecycle measures (RSI, AUCR, and CAR) and four financial measures (ASI, ASR, ACR, and SLR) (Elkins et al. 2013; Proctor, Varma, and Varnedoe 2012; Ram et al. 2023).[26] This process was used to conduct the Federal validation.

Determine and Gather Data Needed for Analysis

This activity involved a process to match the data available from Federal data sources with the information needed to validate the measures. This process involved the following steps (FHWA 2016, 2005):

1. Finalize the list of inputs required to support the validation of the NGPPMs and match the inputs to the data available in the HPMS database and to the outputs from different HERS runs.

2. Gather the data needed to conduct the validation study from HPMS and HERS and link them to data required for NGPPM validation.

3. Identify the substitute missing data, if feasible, and the analytical methods that will be used to address data needs not addressed with existing national databases.

4. Conduct meetings attended by FHWA to address the data issues identified and finalize a data plan for the validation effort.

5. Develop a spreadsheet to hold the required data with notes on different data items, including their availability from HPMS and HERS outputs.

Conduct Feasibility Assessment

Once the data were provided by FHWA, the research team could assess their feasibility for the Federal-level validation. This assessment was done using information extracted from HPMS, data simulated based on the plans finalized in step 1, and various HERS models (e.g., needs analysis and BCR of greater than one) using only data from the State of Idaho. As part of the assessment, the research team compared results from the ITD runs and the HERS outputs (FHWA 2016, 2005).

Document Validation Effort

The last step was to summarize the study performed to include the activities conducted, the validation results, and any recommendations for process changes that may be required to support the use of the NGPPMs.

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[26] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.

DATA AND INFORMATION GATHERING

Data Sources for Next-Generation Pavement Performance Measures Validation

The research team needed to assess the NGPPMs' data needs to apply them at the Federal level. One of the key challenges in this task was the availability of suitable pavement management data at the Federal level. This section summarizes two key data sources that the research team collected national-level pavement data from for the analysis.

Highway Performance Monitoring System

The HPMS is a national-level highway information system that includes inventory information for all the Nation's public roads, regardless of ownership, including Federal, State, county, city, and privately owned roads (e.g., toll facilities). The HPMS data, which are collected, certified, and submitted to FHWA by each individual State, are used for assessing and reporting highway system performance under FHWA's strategic planning process and apportioning Federal-aid highway funds. The HPMS database consists of nearly 70 data fields relating to the extent, condition, performance, use, and operating characteristics of the nearly 140,000 road sample sections included in it. The available HPMS data elements that could be used to support the validation of the NGPPMs at the Federal level were as follows (FHWA 2016):

- Surface type.
- Pavement condition parameters (IRI, present serviceability rating (PSR), asphalt pavement fatigue cracking and rutting, concrete pavement slab cracking and faulting).
- Traffic parameters (past and forecasted AADT, AADT for single-unit trucks and buses, AADT for combination trucks, etc.).
- Functional class.

Highway Economic Requirements System

HERS uses a set of national-level pavement performance models to forecast future pavement condition. HERS models rely on data from the HPMS, which makes the implementation of these models at the national level feasible (FHWA 2016). In addition to the performance models, HERS is also capable of producing some financial metrics, which are related to benefits and costs and might support next-generation financial measures. HERS can run multiple scenarios, ranging from needs analysis to near-optimization using incremental BCA. Even though HERS is not a PMS, the results from HERS can potentially be used to support validation of the NGPPMs at the Federal level as follows (FHWA 2005):

- Incremental BCR of selected improvements. (HERS has a simple list of improvement types, consisting of do-nothing, rehabilitation, and reconstruction.)
- Initial costs and LCCs of improvements.
- User costs.

- Pavement conditions.
- Deficiency ratings.

Feasibility Assessment

Table 15 through table 20 summarize the data required for Federal validation of the various lifecycle and financial performance measures. As can be seen from these tables, some data are not available from HPMS or the results of different HERS runs, thereby rendering directly calculating any of the NGPPMs for the Federal validation infeasible (FHWA 2016, 2005). Recommendations are provided later in this chapter on improving the data availability at the Federal level to allow some of the NGPPMs to be calculated nationally.

Table 15. RSI data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
RSI: Depends on whether RSI will be used for project-level or network-level analysis.	Not applicable	None
Lagging indicators: IRI/PSR; safety (friction/FN); key functional distress types (transverse cracking, raveling); key structural distress types (asphalt pavement fatigue cracking and rutting, concrete pavement slab cracking, faulting, and spalling)	HPMS data elements include IRI/PSR, fatigue cracking, rutting, slab cracking, and faulting (FHWA 2016. Remaining data items may be available for some States but are not available at the Federal level.	“Lagging” indicator pavement condition data are mostly available. For instance, under HPMS, States are required to collect/report roughness, rutting, fatigue cracking, faulting, and slab cracking (FHWA 2016. Beyond these data, most States also collect raveling, spalling, and other cracking data. Friction data are collected at the network level by only a few States.
Leading indicators: Pavement structural capacity measures	Available in some States, not available at the Federal level. Each of these indicators can be obtained using both RWD and TSD devices. More work is required to better model structural performance and, in turn, identify structural treatment types and timings for use in RSI.	The issues surrounding this measure primarily relate to the availability of leading-indicator structural capacity data. Depending on the size of the network and agency testing protocols, the additional cost for network-level TSDD testing is too much. Not available at the Federal level.
Traffic (past and forecasted)	Available	None
Pavement type and structure (i.e., material layers and thicknesses)	Available	None
Pavement age	Available	None

Table 16. ACLM and AUCR data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
ACLM: Optimized lifecycle strategies, including treatment strategies, treatment cycles, costs, and performance prediction models. These data should be programmed into the agency's PMS and BMS, or the agency should have the capability to model the data using other means. AUCR: In addition to the ACLM data needs, agencies will also need to collect and store data on programmed annual costs and actual annual costs at the network level for each asset to compute AUCR.	ACLM and AUCR: Not feasible for Federal validation.	EUAC is a calculation that converts a timestream of costs and benefits into annualized present-value dollars over the lifecycle of an asset. All cost investments required for maintaining an asset in serviceable condition during its lifecycle should be considered. Therefore, all costs that occur within the analysis period should be included, such as the costs for original construction or reconstruction and past or future maintenance, preservation, and rehabilitation costs associated with surface and structural repairs. The ACLM is computed each year and tracked over time for cost trends, but the AUCR requires an additional calculation consisting of two alternatives.
ACLM and AUCR: Data sources.	ACLM and AUCR: AASHTO Red Book, PMS and BMS, cost estimate reports and bid tabs, maintenance and rehabilitation policy, and decision trees (AASHTO 2010).	None

Table 17. CAR data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
The data and calculations needed for CAR are similar to the data and calculations needed for AUCR.	Not feasible for Federal validation. The optimized lifecycle plan, which can be obtained from HERS runs, is needed to calculate relevant costs (FHWA 2005). However, the problem is getting the data for actual investments on the segments, as these data are not available at the Federal level.	The CAR is the ratio of the NPV of all costs incurred to date to the NPV of the agency's optimized lifecycle plan. It is an effectiveness-based measure that compares an agency's actual investments made to date against the optimized lifecycle strategy that results in the minimum practicable LCC strategy. There are two forms of CAR—short-term accrual ratio and long-term accrual ratio.

Table 18. ASI and ASR data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
ASI: Cost of programmed work and cost of work recommended by the management system. ASR: Cost of programmed work and asset value depreciation by section/segment.	ASI and ASR: Not feasible for Federal validation. The programmed work is a challenge to get.	The ASI is the amount budgeted divided by the amount needed to address the management system treatment selections. It can be calculated on an annual basis or for a particular budget cycle/planning period. The ASR is the ratio of asset maintenance, preservation, and replacement expenditure to asset depreciation for a given time.

Table 19. ACR data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
CRV, annual and cumulative asset value depreciation (for calculating depreciated replacement value).	Feasible, as long as a reliable depreciation model is available. Different depreciation models can be used to examine the sensitivity of ACR to those models.	The ACR is the ratio of the depreciated replacement cost to the current replacement cost of an asset. It is an indicator of the average proportion of as-built (or as-new) condition left in the asset.

Table 20. SLR data needs for Federal validation.

Data Needed To Calculate Performance Measure	Availability	Notes
Unfunded treatment needs, replacement value of the pavement network.	Not feasible for Federal validation. The programmed work and unfunded treatment needs are a challenge to get.	While the ASI aims to evaluate the adequacy of the investments, the SLR looks at the relative changes in the backlog. The measure inherently assumes the agency will not be able to address all the needs identified, which is reasonable given that most transportation agencies are struggling to make ends meet when it comes to keeping assets in an SOGR.

Given the infeasibility of directly calculating any of the NGPPMs, a different approach to completing the Federal-level validation was investigated. This proposed approach assessed the feasibility of comparing the results from the PMS used to calculate the NGPPMs at the State level with outputs from HERS for that same State using two separate runs (FHWA 2005). The first run covered a full needs analysis (address all potential deficiencies in the system). The second run covered projects with a BCR ratio of one or greater (economically feasible projects). The steps in this process and the outcomes from this assessment are summarized as follows:

1. The research team selected the State of Idaho for the analysis because progress was being made on calculating the State-level NGPPMs. Data from the ITD's PMS runs were requested, and two spreadsheet files were provided, corresponding to a budget of $130 million: worst-first strategy and maximum-benefits strategy. An example of the data provided is shown in table 21.

2. The research team requested data from HERS runs from FHWA (FHWA 2005). This request was for the State of Idaho, using the most recent HPMS data (2020) to be as compatible as possible with ITD pavement management data (FHWA 2016). The research team provided the following requirements to FHWA (example summaries are shown in table 21 and table 22):

    a. Use the HERS default parameters (for Federal-level validation purposes) (FHWA 2005).
    b. Use a 1-year funding period (HERS uses a 5-year funding period) (FHWA 2005).
    c. Use a 20-year analysis period (the maximum number of analysis years in HERS) (FHWA 2005).
    d. Conduct two runs, one involving a full needs analysis and the other using a minimum BCR of one.

Table 21. ITD maximum benefits strategy corresponding to $130 million budget (data source: ITD).

Benefit	Benefit Alt. 1	Record No.	Deficient (Cracking, Ride, Rut)	Deficient (OCI, IRI, Rut)	Friction Number	Joint Distress Index	Year of Most Recent Preservation	Year of Most Recent Rehab/Recon	Statewide Data Owner	Structural Distress Index	Backlog Treatment
1184.63	1327	67	Yes	No	40	100	2015	2007	ITD	97.62	Preservation—Flex
1788.31	1327	68	Yes	No	40	100	2015	2017	ITD	96.48	Resurfacing—Flex
1842.35	1327	69	Yes	No	40	100	2015	2017	ITD	96.82	Resurfacing—Flex
2204.98	2204.98	70	Yes	No	40	100	2015	2017	ITD	100	—
1584.49	1606.37	71	Yes	No	40	99	—	2012	ITD	100	Preservation—Rigid
1584.49	1606.37	72	Yes	No	40	99	1985	2011	ITD	100	Preservation—Rigid
1004.75	1613.49	84	Yes	No	40	100	2014	1946	ITD	90.98	Restoration—Flex
2204.98	2204.98	85	Yes	No	40	100	2011	1974	ITD	100	—
1327	1327	86	Yes	No	40	100	2012	2012	ITD	100	—
1327	1327	87	Yes	No	40	100	2012	2012	ITD	100	—
1327	1327	88	Yes	No	40	100	2015	2015	ITD	100	—
1327	1327	89	Yes	No	40	100	2017	1997	ITD	100	—
1327	1327	90	Yes	No	40	100	2017	1997	ITD	100	—
997.34	1327	91	Yes	No	40	100	2017	1997	ITD	97.11	Resurfacing—Flex
780.59	—	92	Yes	No	40	100	2018	2007	ITD	97.3	—
1217.27	1327	93	Yes	No	40	100	2018	1968	ITD	95.6	Resurfacing—Flex
849.38	1613.49	73	Yes	No	40	100	2005	2004	ITD	90.03	Restoration—Flex

—No data.

Alt. = alternative; recon = reconstruction; rehab = rehabilitation.

Table 22. HERS summary output (needs analysis)—conditions at beginning of analysis period (FHWA 2005).

Metric	Rural					Urban						Total
	Int.	OPA	MA	Maj. C.	Total	Int.	OFA	OPA	MA	Collector	Total	
Miles	519	1,770	1,464	5,943	9,697	92	29	434	666	773	1,995	11,693
Lane-miles	2075	4,069	3,019	1,1901	21,065	456	103	1,236	1,649	1,564	5,010	26,076
Average IRI (inches per mi)	68.1	78.9	85.6	111.4	81.6	78.1	80.6	121.4	115.9	136.4	109.1	94.4

Int = interstate; MA = minor arterial; Maj. C. = major collector; OFA = other freeway arterial; OPA = other principal arterial.

Table 23. HERS summary output (needs analysis)—conditions after year 1 (FHWA 2005).

Metric	Rural					Urban						Total
	Int.	OPA	MA	Maj. C.	Total	Int.	OFA	OPA	MA	Collector	Total	
Miles	519	1,770	1,464	5,943	9,697	92	29	434	666	773	1,995	11,693
Lane-miles	2,075	4,218	3,144	1,1947	21,386	573	124	1,596	1817	1632	5,742	27,219
Average IRI (inches per mi)	61.3	61.7	68.5	73.1	64.5	58.9	62.2	61.3	62.8	70.8	62.1	63.4

During the investigation, it was learned that the HERS output had recently changed, such that only IRI data were included. In 2018, FHWA initiated a study to update the HERS models to produce other distress outputs, but that effort had not been completed at the time of this writing (FHWA 2005). The HERS update is titled Development of Models and a Framework for a Unified Pavement Distress Analysis and Prediction System (UPDAPS) (U.S. DOT n.d.). This effort falls under the Validation and Proof Testing of Mechanistic-Empirical Based Approach for National Level Pavement Performance Analysis project, which may have the potential to improve the feasibility of calculating the RSI NGPPM (FHWA n.d.b).

Also, although the Idaho HPMS data and ITD pavement management results data were provided using geographic information systems to facilitate linking, that process proved infeasible due to the lack of a common referencing system (FHWA 2016).

VALIDATION ANALYSES AND RESULTS

The Federal validation of the NGPPMs was intended to assess the ability to implement the measures at the national level and thereby improve the reporting and investment strategy analyses at a wider scale. The NGPPMs provide a powerful way to enhance how agencies both make pavement investment decisions at the State level and also assess them at the national level. Unfortunately, the Federal-level validation assessment proved infeasible due to the limited available data at the Federal level to support the calculation of the NGPPMs.

Study results indicate that two of the seven NGPPMs hold the most promise for implementation and use at the Federal level. These measures are as follows:

- RSI: Relies on leading and lagging performance indicators. HPMS provides data to support most of the lagging performance indicators, and HERS provides information on deterioration (based on the AASHTO Pavement ME Design models) (FHWA 2016, 2005; AASHTO 2022). Computation times associated with calculating network-level LCCs for the optimal strategy and all feasible suboptimal strategies are high, making RSI infeasible for Federal validation at this point.

- ASI: Works as leading indicator (when comparing planned investments to management system recommendations) and lagging indicator (when comparing actual investments to management system recommendations) (Proctor, Varma, and Varnedoe 2012). Management system recommendations can potentially be available through the use of HERS and one of its models (mostly BCR of greater than one), but the challenge of determining planned or actual investments makes this measure infeasible at the time of this writing.

VALIDATION STUDY RECOMMENDATIONS

The following recommendations provide a road map for FHWA to enhance the availability of national-level data to support the calculation of some of the NGPPMs:

- FHWA's UPDAPS project is expected to enhance HERS pavement models and produce pavement distress and IRI data (current and projected) (U.S. DOT n.d.; FHWA 2005). These contributions will increase the feasibility of calculating the RSI lifecycle performance measure.

- Additional data are needed to support some of the leading condition indicators dealing with structural capacity. State DOTs are collecting more structural data, and the technology for collecting network-level structural capacity is improving. This trend is similar to the shift around 10 years ago toward network-level distress data collection. State DOTs are using automated distress data collection to meet FHWA reporting requirements and calculate national performance measures. Those requirements can be expanded to include structural evaluation in the future. This inclusion will facilitate the calculation of the RSI lifecycle performance measure.

- Challenges are present at multiple levels in terms of the financial performance measures. To overcome these challenges, HERS needs some enhancements to allow it to consider the data requirements of the financial measures (FHWA 2005). FHWA's UPDAPS project might provide the venue to make those changes (U.S. DOT n.d.). Other challenges are related to reporting requirements, which will need changes to increase the feasibility of calculating the financial performance measures. Following are the reporting requirements:

    - State DOT's planned or actual investment information: This data item will have to be specific to the State-owned system. Some of this information may be available as part of the TAMP, but it may need to be updated on a more frequent basis.

    - Programmed work: This data item's availability will facilitate calculating multiple financial performance measures. Programmed work is purely a State DOT activity. State DOTs produce short-term programs as part of their statewide transportation improvement program, which identify specific projects for a period of 3 years to 5 years, depending on the agency. Pulling these data together for the 50 State DOTs and linking the projects to HPMS segments (for HERS runs) would be a monumental task. Changes are needed to make these data more feasible to share and integrate into the HPMS (FHWA 2016, 2005).

- State-level NGPPMs: If all the States calculated NGPPMs for their networks, then it would become feasible to summarize the information at the Federal level. This approach might be the most feasible choice to produce the NGPPMs at the national level, given the multiple data challenges discussed. The State-level NGPPMs will be reported to FHWA as part of the TAMP reporting requirements or as part of HPMS (FHWA 2016).

CHAPTER 9. IMPLEMENTATION APPROACHES AND SUGGESTED PAVEMENT MANAGEMENT FUNCTIONALITY IMPROVEMENTS

IMPLEMENTATION APPROACHES

Overview of Current Pavement and Asset Management Practices

Transportation agencies have taken a variety of approaches in the implementation and development of their PMS. Some agencies, like SDDOT, have been continually refining their data, models, and software for decades. Other agencies, like ITD, are in the process of transitioning to a comprehensive new PMS. The establishment of minimum requirements for PMSs (23 CFR 515.17) and national performance measures for pavement condition (23 CFR Part 490 Subpart C) have provided a consistent framework from which pavement management operates, especially for pavements on the NHS (CFR 2021c, 2017a). However, since a PMS is frequently used to manage an entire State-maintained pavement network, there is variability in how agencies configure and use nonregulatory condition measures, decision trees, and performance models. Additionally, software vendors take different approaches to recommending and prioritizing treatments and their timing. These differences were also evident from the research team's review of the approaches used by the three agencies who participated in the state validation efforts.

Condition Data and Indices

State DOTs collect a wide variety of distress data. Each of the agencies involved in this study collected data through automated data collection at highway speeds. For decisionmaking, agencies use a combination of distress data and index measures calculated from one or more measures of distress. Table 24 provides an overview of the various distresses and composite condition indexes used by the three agencies that participated in the study. These distresses and indexes were used in addition to the national performance measures for pavement condition defined under 23 CFR Part 490 (CFR 2016a). The composite indices shown in table 24 are specific to each agency and are not necessarily reproducible by other agencies.

Deterioration Models

The agencies involved in this study had each developed deterioration models for specific individual distress indices or distress types, such as the SDI or cracking. The deterioration curves were used to forecast future conditions in terms of each index or distress type. For decisionmaking and analysis, the agencies used the forecasted conditions to determine treatment needs. The forecasted conditions were also used to calculate OCIs, including ITD's OCI. The primary difference between the various agencies was the amount of experience they had with their deterioration curves. SDDOT has been refining its PMS for more than two decades and routinely updates its deterioration curves using a custom analysis tool. This practice provides SDDOT with high levels of confidence in the models and SDDOT's ability to identify changes in pavement performance or data quality over time. In contrast, ITD implemented its system in 2019 and is still using the first generation of deterioration curves. While ITD has confidence in PMS analysis results and recommendations, it has not yet had the opportunity to build additional deterioration curves that consider the impact of past treatments on the performance of potential future treatments.

Table 24. Distress metrics and condition indices used by the State validation agencies.

Agency	AC Pavement Distress Data	PCC Pavement Distress Data	Condition Indices and Roughness
ITD (Poorbaugh 2017)	• Cracking. • Wheelpath. • Block. • Longitudinal. • Transverse. • Fatigue. • Edge. • Patching/patch deterioration/potholes. • Rutting. • Raveling.	• Slab cracking. • Joint seal damage. • Joint spalling. • Faulting. • Map cracking. • Studded tire wear.	Flexible pavements: • OCI (calculated based on fatigue cracking, edge cracking, patch deterioration, transverse cracking, block cracking, and raveling). • SDI (calculated based on fatigue cracking, edge cracking, and patch deterioration). • NDI (calculated based on transverse cracking, block cracking, and raveling). Rigid pavements: • OCI (calculated based on slab cracking, map cracking, joint seal damage, joint spalling, and faulting). • Slab index (calculated based on slab cracking, and map cracking). • Joint index (calculated based on joint seal damage, joint spalling, and faulting).
SDDOT (SDDOT 2023)	• Cracking. • Block. • Transverse. • Fatigue. • Patching and patch deterioration.	• Cracking. • Transverse. • Corner. • D-cracking. • Alkali silica reactivity. • Patching. • Faulting. • Joint seal. • Joint spalling. • Punchouts (CRC pavements). • Block cracking (CRC pavements).	• SCI (calculated based on all distresses). • IRI.
TxDOT (Tx DOT 2022)	• Cracking. • Alligator. • Block. • Longitudinal. • Transverse. • Patching. • Raveling. • Rutting. • Failures.	CRC pavements: • AC patches. • PCC patches. • Punchouts. • Crack spalling. JPC pavements: • AC patches. • PCC patches. • Failed joints. • Shattered slab. • Longitudinally cracked slabs. • Failures.	• CS. • Distress score. • Ride score. • Skid score. • IRI.

AC = asphalt concrete; PCC = portland cement concrete.

Decision Trees

Each agency involved in this study used decision trees for identifying appropriate treatments based on pavement conditions, pavement type, traffic levels, geographic location, and other factors. Each of the three State validation agencies used multiple decision trees to generate potential treatments. However, the various PMSs used the decision trees in different ways. TxDOT and ITD applied multiple decision trees to the data to determine potential treatments. The system then selected the most "significant" of these treatments and disregarded the rest. If no decision tree results in a potential treatment for a given year, the section is given a "no treatment" designation.

In the case of SDDOT, if the multiple decision trees resulted in different treatment recommendations, each of those treatments were considered in the treatment optimization process. This inclusion resulted in considerably more potential treatments being generated by SDDOT's PMS than by the other two State DOT's PMSs.

Treatment Selection and Optimization

The processes used for selecting a suggested set of treatments from among the potential recommendations varied largely based on the design of the commercial software used by the agency. Each of the systems used in the pilot agencies developed more recommendations than could be supported with expected levels of funding. The systems used an artificial measure of "benefit" to identify the type, location, and timing of treatments that provided the most cost-effective investment when all needs were considered.

Typically, the benefit is represented by the additional performance provided by a treatment and is calculated as the area under the performance curve. The benefit calculations are unitless, vary by agency, and are not objectively comparable across agencies because of the differences in indices, deteriorations rates, and so on. Where the PMSs vary the most is in how each system optimizes benefit over the analysis period.

The PMS used by ITD and TxDOT focuses on selecting the best set of treatments for every pavement segment in each year of the analysis period, sequentially. This selection is determined based on conditions in the previous year, either current or forecasted. For each year in the analysis period, the PMS explores all feasible treatment options as dictated by the decision trees for each segment in the pavement network, and the optimization routine determines the best mix of treatments that yields the highest BCR for the budget available. Based on the selected treatments, the system forecasts improved or deteriorated conditions for each segment in the network and repeats the process for the next year of the analysis. This process is repeated, iteratively, for each year of the analysis period.

SDDOT's PMS uses a different approach to determine the best set of treatments in the analysis period. The SDDOT PMS generates a set of potential strategies for the entire length of the analysis period. It considers all possible treatments for the first year of the analysis. Then, following the rules of the decision tree and deterioration models, it determines the potential treatments for the next year for each strategy. Since each of the initial strategies will likely have multiple treatment options in the next year, this action results in the creation of additional strategies. This process is repeated for each year of the analysis until a complete set of potential strategies is established. Notably, this analysis approach is a variation of the RSI approach in that all the potential strategies for each pavement section generated by the PMS decision trees are considered in the multiyear analysis.

This approach differs from the RSI analysis in its use of decision trees rather than consideration of all possible treatment combinations over an analysis period as long as LOS threshold levels for performance indicators that impact road users are not exceeded to identify potential strategies. Through this process, the system generates a significant number of potential strategies for each segment, often in excess of 100 for a 10-year analysis. The next step of the analysis process is to apply a budget and a timeframe to the treatment selection process. The system then uses a process of incremental benefit cost optimization to determine the mix of strategies that results in the greatest overall benefit for the analysis period within the available budget. To help reduce the number of strategies that are considered in the analysis, the program uses the concept of an "Efficiency Frontier," which reduces the number of possible options to those with the highest return. Strategies determined to be under the Efficiency Frontier can be eliminated from consideration since their benefit is suboptimal to other strategies. The system also includes the ability to allow the budget to be held constant within each year of the analysis period or "float" between years. Allowing the budget to float between years also reduces the number of calculations needed to maximize the benefit.

Implementing Next-Generation Pavement Performance Measures

The NGPPMs discussed in this report are primarily intended to help transportation agencies answer the following questions:

- Are we investing adequately in our infrastructure?
- Are we making sound, long-term decisions with planned investments?

The research team identified three main challenges associated with the implementation of the NGPPMs based on the three State DOT validation efforts conducted as a part of this study: determining the need, determining asset value depreciation, and calculating LCC.

Determining the Need

Establishing the true pavement need is a challenging process. The approaches vary from agency to agency. In simple terms, some agencies may consider the need to be the amount of funding needed annually to meet or exceed the desired SOGR over a chosen analysis period. Other agencies may define need as the funding necessary to fix each pavement section that is suggested by the decision trees in the current year. One of the main issues associated with determining the true need is that it varies from year to year, based on what projects were actually implemented by the agency. If the feedback loop from the project delivery process to the pavement management process is not robust or does not exist, the need calculations performed using the data stored in the PMS are likely to be inaccurate. The main challenge with the need parameter is that not all PMSs calculate and report this variable.

Determining Asset Value Depreciation

Determining the pavement need has similar challenges to those seen with asset value depreciation. Agencies may choose different approaches to calculate depreciation (e.g., straight line models, condition-based trends). As with need, asset value calculations are not a direct output from existing PMS tools.

Calculating Lifecycle Cost

Most PMS tools available at the time of this writing simply report the summation of treatment costs over the analysis period considered as the total investment need associated with a particular analysis run. These tools do not calculate project- or network-level LCCs. Also, the RV of treatments beyond the analysis period or the investment required at the end of the analysis period to restore the pavement network to the desired SOGR is not typically calculated or reported.

Even though the need, asset value, and LCC calculations are not explicit outputs from a PMS, they can be computed using simple spreadsheet-based tools that are customized to reflect agency practices. However, to simplify the implementation process and promote widespread adoption, these parameters should ideally be calculated and reported by the PMS.

Practical Implementation Strategies

There are some challenges associated with implementing the NGPPMs in today's pavement management environment. However, even without a full implementation, State DOTs can start using these measures in conjunction with traditional condition-based measures to better understand their usefulness in the pavement management decisionmaking process. Some short- and long-term strategies for practical use are as follows:

Short-Term Strategies (Less Than 5 Years)

- Calculate the NGPPMs and compare the results to existing agency-based condition measures to see if the measures can help narrate another account.
- Use the measures to communicate differences between various treatment strategies and funding levels evaluated by the agency for a nontechnical audience.
- Pilot the NGPPM use within a district/county within a State to validate treatment decisions.
- Conduct training for PMS practitioners on how the measures can be implemented in the present through the development of simple tools that can be used in conjunction with PMS data.

Long-Term Strategies (5–10 Years)

- Work with the PMS vendor to make necessary adjustments that will enable the calculation of the measures within the PMS without the need for other supplemental tools.
- Use performance measures to validate pavement management decision trees. Is the PMS recommending the right type of treatment at the right time? Will its recommendations help offset asset value depreciation over the long term?
- Improve measure computation accuracy to make it more representative of actual values through refinements of PMS data and model inputs.

Implementing Transportation Asset Management Methodology

The next-generation TAMM was conceptualized as a means of integrating multiple asset classes within appropriate common business processes that might be implemented within the next 10 years using data and tools likely to be available within that timeframe. These cross-asset business processes included determination of funding levels, network policy formation, resource allocation, project development, priority programming, and delivery. Implementation feasibility was a central concern in the TAMM's development, leading to decisions to keep the framework as simple as possible and rely on existing systems as much as possible.

Any type of analytical decision support is predicated on the desire by an agency to adopt data-driven, result-oriented planning processes involving all types of infrastructure assets. The need for simplicity focused attention on identifying or developing appropriate performance measures for comparing strategies within the TAMM. The suggested measures are data-driven because they are meant to be computed in a uniform way using consistent data regardless of asset class. They are also limited by the availability and quality of data. They are result-oriented in that they support a style of decisionmaking that evaluates alternatives based on the future outcomes they are likely to produce, using data-driven models to forecast those outcomes.

The models used in the TAMM relied on forecasts of future conditions that were based on assumptions about actions an agency would take, costs associated with these actions, and their expected effects on performance. The forecasts of future actions were carefully described as selections and not as recommendations. The models selected actions based on a simulation of the types of actions that might be expected for a particular strategy, such as minimizing long-term costs. Since they are based on simulations, the models are meant to be used for decision support, not decisionmaking. The models help make data more useful but are just a subset of the important considerations in making TAM decisions. They are useful within the type of performance-oriented culture that asset management is meant to foster, where decisionmakers demand the best practical information, ensure they have the tools to provide it, and actively use it in making their decisions.

Practical Implementation Strategies

The proposed tradeoff analysis tool is a simple tool that uses sorting and summarization methods widely found in capital programming spreadsheets and readily supported by common software. The TA-MAPO tool was developed as a proof of concept for the cross-asset tradeoff analysis and can potentially be implemented by transportation agencies in the short term. However, agencies are more likely to adapt the methods used in TA-MAPO in the long-term for incorporation into already existing information systems to support various asset management planning processes. For example, all State DOTs have sets of reports (usually in internal agency formats evolved over many years of use) that are essential for their annual or biennial budgeting and programming activities. Agencies may find that incorporating the proposed TA-MAPO within the existing system is easier than re-creating these reports in a new system. Any implementing agency may want to consider this approach, perhaps using the TA-MAPO tool as a working prototype (FHWA 2024b).

If an agency's current process for budget allocation is simply the continuation of historical norms, then the idea of using a tradeoff analysis may be new. Using a tradeoff analysis requires a willingness among stakeholders to consider changes in historical allocations, which may also imply changes in staffing and other resources and affect the workload of the contractor community. The impacts of such decisions are much bigger than the scope of existing management systems. Using an economic performance measure to evaluate tradeoffs is valuable, in part, because of the ability to estimate the economic benefit of a change in historical norms, which can be weighed against the costs. A tool like TA-MAPO can be used to explore multiple scenarios, including the possible need to implement funding allocation changes in successive phases to provide the agency and industry the time needed to adapt (FHWA 2024b).

SUGGESTED PAVEMENT MANAGEMENT ENHANCEMENTS

Enhancements To Advance Use of Next-Generation Pavement Performance Measures

Inherent challenges exist in fully implementing the NGPPMs that are related to two aspects: the way the PMS software has been designed and the way it is being used within an agency. The following suggestions are offered to help advance the future implementation of the NGPPMs. These suggestions promote the following features within PMS tools:

- The ability to calculate need within the PMS: Calculating annual need to achieve or maintain the desired SOGR at the network level for each analysis run conducted using the PMS will greatly simplify the process to calculate financial measures. For an agency, it is important that a strong feedback loop be established to ensure the PMS analysis reflects actual conditions in the field from both a structural and functional perspective. For PMS developers, it is important that pavement needs are calculated in each year of the analysis and stored in a way that can be used to determine several NGPPMs.

- The ability to estimate asset value depreciation within the PMS: If the analysis module within the PMS has tools to model asset valuation and asset value depreciation using one or more approaches, then the calculation of financial measures and other measures or prioritization methodologies based on LCC are significantly simplified. Storing these values and making them available to the user is also important.

- The ability to calculate LCC within the PMS: Typical PMS software tools do not calculate LCC; they simply report the total cost of treatments over the chosen analysis period. The consideration of the remaining life of a pavement at the end of the analysis period and the types of treatments that might be needed to restore the pavement to the desired SOGR at the end of the analysis period is not typically considered in the total cost of a lifecycle strategy. With the ability to determine true LCC for each multiyear strategy, agencies will be better prepared to compare the long-term impacts of different lifecycle strategies evaluated by the agency.

- The ability to evaluate all feasible treatment strategies without relying exclusively on decision trees: Many of the PMS tools available today can generate multiple treatment strategies for each pavement segment in the network. However, the strategies developed still rely heavily on the rules established using the decision trees. Decision trees rely on predetermined thresholds for distresses, pavement condition, and/or other performance indicators (cracking, rutting, OCI, IRI, etc.). The use of these somewhat-subjective treatment trigger thresholds could potentially result in a true optimal solution being missed. In contrast, the RSI approach allows the consideration of an unlimited number of treatment combinations over an analysis period as long as LOS threshold levels for performance indicators that impact road users are not exceeded. This subtle shift in approaches helps to ensure that the true optimal strategy from an LCC perspective is identified and, under constrained budgets, alternate suboptimal strategies can be evaluated in terms of the resulting increase in LCC.

- The use of structural health data to model asset valuation: Current approaches to estimating future pavement conditions rely on surrogate distress types (e.g., fatigue cracking) to represent the structural health of a pavement. However, surface cracks are no longer a reliable indicator of structural condition or pavement structure health since the advent of effective pavement preservation strategies. These strategies include intervening early to preserve and extend pavement life as well as increasing the thickness of long-life pavements. NGPPMs that rely on asset value calculations may overestimate actual conditions due to a lack of inadequate information on underlying pavement structure conditions. Agencies can improve their overall decisionmaking by using the NGPPMs to add assessments of pavement structural health using technologies like TSDDs and the data from these technologies to develop asset valuation models tied to pavement structural health.

- The availability of robust pavement performance modeling tools: Not all PMS performance models consider the cumulative effect of historical treatments and/or pretreatment conditions in determining future conditions. For instance, if two pavements receive the same preservation treatment, but one was in Good condition and the other was in Fair condition, initial projections for future condition would typically project the same number of years of additional service life. To overcome this limitation, the next generation of PMS software tools would benefit from including tools that can model performance while considering pretreatment structural and functional conditions.

- The availability of dedicated staff for pavement management data analytics: Staffing has always been a challenging issue for State DOTs. Agencies are already dealing with huge volumes of data, and the amount of data is only expected to increase in the future. This situation may impact some agencies' abilities to operate their PMSs, especially if staff has myriad duties that limit the amount of time spent on configuring the pavement management software to address desired changes in functionality. The ability to have a dedicated group of agency staff primarily focused on converting all the data collected (current and historical) into useful information that can be leveraged in the PMS to support decisionmaking is expected to be helpful in the future.

Addressing these suggestions for advancing the ability of pavement management software to fully implement the NGPPMs will enable agencies to realize an enhanced ability to assess and compare pavement management strategies and make decisions that are not only cost effective in the short-term but also provide the best return on investments over the lifecycle. The main benefits that can be realized through the implementation of the NGPPMs are summarized as follows:

- Identify pavement treatment strategies that result in the lowest practicable LCC: The lifecycle approaches and measures evaluated and validated through this project (RSI, CAR, and AUCR) will help agencies assess the effectiveness of the pavement management strategies selected by comparing the planned expenditures and performance outcomes to the optimized strategy. This comparison will help agencies make necessary adjustments to the strategies as they are being implemented to ensure deviation from an optimized strategy is minimized.

- The use of NGPPMs may help agencies communicate stories that may not be apparent from just condition-based indicators. Financial measures, such as ASI, ASR, and SLR, will help agencies evaluate the effectiveness of planned investment approaches in meeting and sustaining the desired SGOR. Additionally, these measures will indicate the impacts of agencies' planned investment approaches in maintaining asset value and keeping the backlog growth rate in check. The time-series trends demonstrated by these measures can help identify if and when a significant shift in the pavement management approach may be needed.

- Communicate performance outcomes using measures that resonate with decisionmakers: The use of traditional performance measures, such as IRI, pavement distresses, and OCIs, may not necessarily resonate with decisionmakers within agencies. The financial measures evaluated in this study communicate pavement network performance using simple, intuitive indicators that do not require specialized pavement management knowledge.

- Use measures for cross-asset tradeoff analysis: Since all the performance measures evaluated in this study are dimensionless or asset-generic, a main benefit is the potential to use these measures for cross-asset tradeoff analysis to evaluate the long-term impacts of different treatment strategies and funding allocation approaches.

Enhancements To Advance Use of Transportation Asset Management Methodologies

The complex part of agencies implementing the proposed TAMM is computing the required performance measures, including forecasts of outcomes and the benefit-cost priority measure. In the pilot studies, the research team generated the calculation outside the management systems in a manner considered temporary, using iterative processes for pavements and an open-source spreadsheet for bridges. Appendix E describes the methods used. These methods did not work as well as the research team expected (especially for pavements) due to a lack of necessary models within PMSs. A better approach is to enhance the PMS and BMS analyses and reporting capabilities to perform the necessary analyses of LCCs and user costs. These results could then be available to outside programs for other purposes, including cross-asset tradeoff analysis. Such models are valuable for many purposes in pavement and bridge management because they fully reflect the economic benefits of infrastructure renewal work.

The TA-MAPO tool includes a working prototype of an investment candidate file, which system developers can use to help them design an output format for the necessary data (FHWA 2024b). In some cases, existing management systems may already perform the necessary calculations and merely need an appropriate format for exporting the results. Other cases may be more complex—especially in a PMS, where safety and mobility are reflected only in constraints rather than as user costs. The biggest problem noted in the pilot studies was the challenge in using the PMS to fully account for the benefits of pavement work beyond improvements to condition.

Developers are often concerned about the computational intensity of a long-term economic analysis. Remarkably, this concern has been a constant for more than 40 years. Such tools have long been in common use, even as the speed of computers has increased by many orders of magnitude. User expectations of such tools may be increasing as fast as processor speed, leaving widespread implementation constantly just beyond the horizon and allowing for further delays in adoption. Existing software tools, such as HERS, NBIAS, and StruPlan, show that execution times can remain reasonable as long as system requirements are appropriately bounded and modern computational techniques and algorithms are used (FHWA 2005; Thompson 2021).[27]

The research team found few examples of asset management systems for asset classes other than pavements and bridges that were capable of performing the necessary analysis. The main exceptions were systems used by agencies that incorporated nonbridge structures, such as tunnels, sign supports, and retaining walls, within their BMS. The proposed methodology is especially suitable for asset classes where preservation is a common action. Aside from nonbridge structures, these asset classes may include unstable slopes, buildings (including rest areas), drainage facilities, intermodal facilities, signage, and barriers.

The benefits of making the functional changes to support the proposed next-generation TAMM lie in the ability to manage an infrastructure network as a whole, maintaining an appropriate balance in resource allocations and performance among all the components of the network. This balance helps to ensure that the desired LOS is provided at the lowest long-term cost, considering the differential levels of deterioration rates, cost, and risk that exist within the network. Elements of these benefits include the following:

- Existing management systems can advance on their own lifecycles independently as they had been, taking advantage of the long-standing frameworks, expertise, training, tools, and research existing within each disciplinary area.
- Network component performance differences are evaluated objectively and equalized to the extent appropriate to best serve public needs.
- Internal network performance differences are justified based on objective analysis, helping the agency to avoid unintended misallocation, especially among socio-economic classes of users or geographic areas.
- Transportation funding increments are allocated to the parts of the network that can most effectively use them to improve network performance.
- Long-term costs to keep their networks in service are minimized.
- Infrastructure renewal benefits are estimated more consistently and completely and are more easily communicated to stakeholders.
- Risk of extreme events, climate change, and advanced deterioration are allocated and balanced in a consistent way across all network components.

All these benefits are an intrinsic part of the promise of asset management—a promise which the proposed methodology will help to realize.

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[27] FHWA. 1999–2024. *NBIAS* investment analysis tool (software).

CHAPTER 10. FINDINGS AND CONCLUSIONS

FINDINGS

The objectives of this project were to develop, test, and validate several promising NGPPMs and a proposed TAMM and to develop and provide guidance related to modifications needed to existing asset management systems to implement the technologies and LCP concepts. To accomplish these objectives, the research team performed a series of tasks involving the development and refinement of the technologies and testing and validation analysis at three selected State DOTs and at the Federal level. The key findings from these activities are presented in this section.

Next-Generation Pavement Performance Measures

Table 25 summarizes the key takeaways and validation experiences associated with each performance measure evaluated in this study. From a whole-life perspective, the RSI framework is the most robust analysis approach that can help agencies establish long-term treatment strategies that are most cost effective. That said, the RSI approach is computationally intensive, and the analysis can be time consuming. Additionally, a learning curve is associated with implementing this approach within State DOTs. However, it is expected that computational resources will continue to improve over time, and the processing power of computers 5 to 10 years from now could significantly reduce the time required to conduct the RSI analysis. The RSI approach will help advance the state of the practice in the following ways:

- Evaluate the impact of all feasible treatment type and timing combinations without limitations imposed by decision trees.
- Make the treatment decisions based on LCCs.
- Consider the short-term and long-term impacts of deviating from the lowest LCC strategy (optimized strategy) proactively.
- Support the pavement LCP activities required by 23 CFR Part 515 (CFR 2021b).

Table 25. Strengths and implementation challenges for each NGPPM evaluated.

Approach/ Measure	Summary	Testing and Validation Experiences
RSI	Reduces reliance on decision trees for treatment selection (Ram et al. 2020). Identifies the lowest LCC strategy that meets established objectives and performance requirements under constrained and unconstrained budget situations (Ram et al. 2020).	Developing optimized models can be difficult if the pavement management practices at an agency are not currently considering LCCs. Analysis runs are time- and resource-intensive. Output dataset requires more storage space.
AUCR	Since AUCR is a relatively simple measure that compares the annualized costs of current strategies to the optimized strategy, it is likely to be intuitive to decisionmakers.	Calculating the AUCR requires identifying the lowest LCC strategy using either the RSI analysis or other methodologies. Agencies need to conduct additional work in determining a level of acceptable deviation from the optimized plan and its implications.
CAR	Helps in visualizing the deviation from the optimized strategy and the short- and long-term differences in spending when comparing multiple lifecycle strategies.	Calculating the CAR requires identifying the lowest LCC strategy using either the RSI analysis or other methodologies. Agencies need to conduct additional work in determining the level of acceptable deviation from the optimized plan and its implications.
ASI	Can be used to monitor different aspects that determine asset performance (maintenance, preservation, etc.) (Proctor, Varma, and Varnedoe 2012). Can be compared across different asset classes (Proctor, Varma, and Varnedoe 2012). Can be used to establish short- and long-term investment targets at both the agency and district levels that will help the agency meet or exceed the desired SOGR (Proctor, Varma, and Varnedoe 2012).	The ASI requires calculating the need, which can be challenging.
ASR	Indicates if an agency is investing adequately to offset asset value depreciation (Ram et al. 2023). Can be compared across different asset classes (Ram et al. 2023). Can be used to establish targets that will help keep the asset value depreciation rate in check (Ram et al. 2023).	Calculating asset value depreciation can be challenging and approaches can vary significantly across agencies. Can help agencies narrate an account that may be different from what the condition trends may show.
ACR	Indicates proportion of as-new condition left in the assets (Ram et al. 2023). Can be compared across different asset classes (Ram et al. 2023).	Calculating asset value depreciation can be challenging, and approaches can vary significantly across agencies. The ACR does not help to communicate any different information than condition-based measures communicate.

Approach/ Measure	Summary	Testing and Validation Experiences
SLR	Time-series trends can help track progression of backlog when compared to a baseline established by the agency (Ram et al. 2023).	If an agency's PMS does not report a backlog, calculating this measure can be difficult. The SLR can help determine whether a significant shift in treatment strategies may be needed to help keep the rate of change of backlog in check.

FHWA recently published a white paper on the RSI approach that provides a simplified overview of the fundamental concepts associated with RSI (Ram et al. 2021). This document provides suggestions on how agencies can start considering the RSI approach to pavement LCP.

The other lifecycle measures evaluated in this study (CAR and AUCR) can be used in conjunction with the RSI analysis to help visualize how different lifecycle strategies compare against the optimized strategy. The three financial measures that proved to be most useful include the ASI, ASR, and SLR. When used in concert, these leading measures can help answer the following questions:

- What percentage of the PMS's optimized program is needed to achieve and/or maintain the desired SOGR?
- What amount of the budget needs to be invested to offset asset value depreciation?
- What types of investments need to be made in terms of treatments that help offset depreciation? (Rather than only asking what investment level is needed.)
- At what point in the investment approach is a significant shift considered to ensure acceptable long-term performance?

In the absence of network-level pavement structural condition information, the ASR can also potentially serve as a surrogate measure for structural health if the asset value calculations are modeled based on predicted structural distresses (e.g., rutting and fatigue cracking).

The ACR measure provides some useful information from a communication standpoint (e.g., what fraction of the as-built condition is left?). However, this account is no different from what conventional condition measures, such as IRI and composite indices, help to communicate. Hence, agencies may not find this measure appealing.

Lastly, all the financial measures evaluated in this study are dimensionless; therefore, they can be expanded to other asset classes beyond pavements.

Proposed Transportation Asset Management Methodology

Transportation agencies own, operate, and maintain a diverse infrastructure to support the provision of transportation service to the public, including pavements, bridges, tunnels, earthworks, drainage facilities, guardrails, traffic control devices, lighting, and buildings. All these asset classes work together as an infrastructure network. However, each asset class has its own technologies and specialized maintenance requirements, and the performance of each asset class affects the public in its own ways.

Because of the specialized technologies and professional disciplines required to construct and maintain the various classes of physical assets, transportation agencies have traditionally managed them separately. Over time, each asset class has evolved its own conceptual frameworks, research concerns, training requirements, technical jargon, and performance metrics. This diversity makes it challenging to develop practices and tools that leverage the great strengths of the separate technical disciplines while enabling the integrated management of the infrastructure network as a whole.

This study was charged with developing a tradeoff analysis methodology that can serve the diversity of asset classes and cut across their boundaries to support business processes that manage the infrastructure network as a whole. In the interest of implementation feasibility, the methodology was conceptualized to rely on existing management systems to the fullest extent possible and focus on a performance measure that can be used to prioritize investments and allocate resources fairly across all classes of assets. Such a measure could then be used in planning tools already familiar to transportation agencies to serve the relevant business needs. The search for this measure produced the following findings:

- The research team facilitated a focus on the network as a whole by concentrating on existing Federal legislation and rules that agencies already observe that cut across asset class boundaries. These laws and rules include the statement of national transportation goals in 23 USC 150(b), the requirements of transportation performance measures in 23 CFR 490, and the requirements of management systems in 23 CFR 515 (CFR 2021a, 2016a, 2021b).

- Many State DOTs have legislation or strategic plans that closely follow the national goal areas, particularly condition, safety, mobility (for people and freight), and environmental sustainability. Some agencies have additional objectives for factors such as customer satisfaction. Different asset classes affect these objectives in different ways. In some cases, the objectives are taken as constraints rather than variables to be optimized. For example, PMSs often do not attempt to quantify the mobility benefits of projects, but merely apply constraints to limit mobility impacts of deteriorated conditions.

- 23 CFR Part 490 includes the Federal transportation performance management rules, which precisely define condition measures that are well-established in current practice and support certain essential processes, such as tracking trends and managing targets (CFR 2016a). The pavement and bridge measures are superficially similar in that they both are weighted averages of the assets in Good or Poor condition. However, the definitions of Good and Poor fundamentally differ among asset classes, so these measures are not comparable across asset classes and cannot be used to compare dissimilar investments or to provide a basis for resource allocation. Further, these measures are defined for pavement and bridge conditions only, and not for other asset classes or other performance concerns.

- 23 CFR 515.17 includes Federal management system requirements that reflect existing agency requirements and long-standing research, particularly the practice of LCCA, risk management, and benefit-cost priority setting (FHWA 1998; CFR 2021c). However, many existing management systems, especially PMSs, are not configured by the agency for LCCA or risk analysis.

- The research team reviewed the current state of practice and did not find commonly used asset management systems to offer a performance measure that could be interpreted consistently across asset classes for the purpose of tradeoff analysis. This inconsistency was also true of the NGPPMs described in this report. Although certain related software programs, such as FHWA's HERS, have some of the capabilities needed, they lack other capabilities required for lifecycle analysis and preservation planning (FHWA 2005). Moreover, existing management systems may have the data and basic analysis capabilities needed to derive a usable performance measure.

- Decision trees often represent transportation goals and objectives as constraints rather than as variables to be optimized. This style of representation limits the ability to readily perform a tradeoff analysis that investigates a range of alternative resource allocations among asset classes or among performance concerns. This architectural feature of many PMSs makes it difficult and time-consuming to develop a sufficient range of scenarios to support cross-asset tradeoff analysis. This issue is less prevalent with BMSs, because they were initially designed to work with highly diverse inventories (including nonbridge structures) and to model performance concerns other than condition.

The barriers to improved management system capabilities in support of cross-asset tradeoff analysis are found on both the supply side and the demand side of the economic equation for management system developers. On the supply side, no standard framework for the data needed to support cross-asset tradeoff analysis exists. Thus, developers lack a data model and analytical process that is sufficiently stable to spread the cost of developing it over multiple agencies.

On the demand side, the agency decisionmakers selecting management systems are either pavement experts or bridge experts, rarely both. This expertise in both areas is beneficial. However, cross-asset tradeoff analysis requires a third area of expertise that is not often recognized, an understanding of system capability. A lack of awareness is likely among agency programming staff regarding the fact that cross-asset tradeoff analysis is feasible as an application that is piggy-backed onto existing management systems.

Reflecting both supply and demand, developers most likely need certain areas of expertise to develop appropriate features for cross-asset analysis. The most important areas are as follows:

- Sufficient cross-disciplinary understanding and experience with multiple asset classes (including pavements and bridges) from a program management or research perspective.

- Lifecycle thinking, especially as practiced for network-level applications.

- User cost models and related methods of econometric analysis of public policy.

- Risk analysis, encompassing the probability of extreme events, the effect of such events on transportation assets, and the resulting disruption to transportation service.

- Software architecture and design expertise with large computational systems to optimize execution efficiency, including algorithm design and multithreaded programming.

These skills do exist and are readily available, but companies developing management systems need sufficient assurance that an investment in these skills will satisfy their business needs. In the transportation industry as a whole, such assurance can be provided by standard-setting processes or joint development projects.

Commercial firms have previously made efforts to gather some of these skills together to develop integrated asset management systems that attempt to serve the needs of pavements, bridges, and other asset classes—all within the same software system. Several efforts were launched in 1991 after passage of the Intermodal Surface Transportation Efficiency Act (U.S. Congress 1991). These approaches have had some degree of success. However, significant differences exist among asset classes in forecasting and engineering technology, and channels of research, training, and conceptual frameworks are largely independent.

CONCLUSIONS

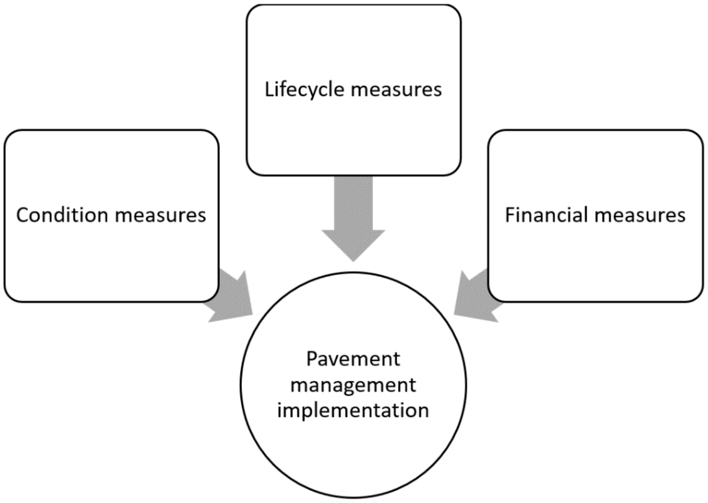
Next-Generation Pavement Performance Measures

Each performance measure discussed in this document can help transportation agencies answer questions that are important to monitoring long-term pavement performance and measuring the overall effectiveness of a pavement management program. To make sound, long-term investment decisions, agencies need indicators of performance in multiple areas to develop a better understanding of pavement performance and investment needs. Figure 55 presents a proposed approach for optimizing pavement management decisions that considers the following aspects:

a. Pavement conditions using traditional measures that are specific to an asset class and agency (e.g., IRI, rutting, cracking for pavements, agency's rating scale of pavements in Good/Fair/Poor conditions).

b. Lifecycle measures that provide information on the LCCs of maintaining a pavement network.

c. Financial measures that describe the financial sustainability of an agency's pavement management program (as discussed in chapter 2).



Source: FHWA.

Figure 55. Illustration. Proposed approach to comprehensive pavement management program implementation.

Condition Measures

Current and projected conditions are the most common indicator of pavement performance. Pavement conditions typically deteriorate over time and with use. Performing preservation, rehabilitation, and reconstruction activities maintains or improves the asset condition -in accordance with the actions performed. Condition is generally considered a measure that is physically observable through a standard rating protocol (e.g., cracking and rutting for pavements). Condition measures are currently used in management systems and are predicted into future years using a deterioration model. This model enables the agency to ascertain the cost-effectiveness of applying treatments at different points in time.

Applying this process to an entire network provides agencies with the information needed to evaluate different investment strategies. The use of properly calibrated management systems enables an observable lagging indicator to be used to predict future performance so that it can guide investment decisions in a way similar to a leading indicator. However, the use of condition-based measures does require the evaluation of a range of treatment strategies and fiscal scenarios over a long analysis period to determine situations that result in the lowest LCC. Other complexities, such as the use of a single overall composite indicator versus the use of condition category ranges based on the composite indicator, need to be understood by analysts and decisionmakers.

Condition measures have evolved over the past several decades. FHWA has published rules for pavement and bridge performance measures (23 CFR 490) that establish standardized measures for characterizing asset conditions. Many condition measures are not comparable across asset classes; however, they can be converted to a Good/Fair/Poor scale using a standard rating procedure that is at least superficially similar across asset classes. The National Performance Management Measures rule (23 CFR 490) provides a standard approach for determining the condition of pavements and bridges using a Good/Fair/Poor rating scale; however, some agencies only use this rating scale for reporting purposes (CFR 2016a). A number of agencies already have a legacy procedure to rate asset conditions and use this measure in their asset management process to make treatment and investment decisions. It is important for agencies to be able to integrate their existing performance measures into the asset management implementation framework.

Lifecycle Measures

Lifecycle performance measures directly relate to the funding level and the quality of the treatment selection process being used within the agency, including the treatment type, timing, and LCCs. Ideally, a PMS recommends treatments at the point when they are most cost-effective. This practice maximizes the benefit provided by the treatment at the lowest possible cost. Missing the window of opportunity reduces the cost-effectiveness of the treatment, thereby increasing the long-term LCC.

The following three lifecycle measures/approaches were discussed in chapter 2 of this document:

- The RSI approach uses a structured sequence of maintenance, preservation, rehabilitation, and replacement actions through LCC considerations to provide acceptable service over the assets' life at minimum practicable cost. It focuses on the when and where aspects of treatment application to iteratively determine the most cost-effective series of treatments to maintain pavements over an extended planning horizon (Rada et al. 2016).

- The AUCR measure is a ratio of the programmed EUAC per lane-mile of all expenditures over the pavement's lifecycle to the optimized EUAC per lane-mile. The measure helps visualize the magnitude of the deviation from the optimized lifecycle strategy using a simple, intuitive metric.[28]

- The CAR measure compares the planned investments in an agency's asset lifecycle strategy to the optimized lifecycle plan for the same asset, which would theoretically result in the lowest LCCs. The CAR can also help evaluate the financial sustainability of different lifecycle strategies evaluated by the agency.[29]

Financial Measures

Financial measures can assist agencies in optimizing their investment allocation decisions. Four different financial measures were evaluated under this study, each of them providing unique information on the financial sustainability of an agency's investment approach. These measures included the following:

- The ASI helps decisionmakers determine the adequacy of investments to address needs identified by the PMS (Proctor, Varma, and Varnedoe 2012).

- The ASR helps decisionmakers determine whether sufficient investments have been made to offset asset value depreciation (Ram et al. 2023).

- The ACR highlights the average proportion of as-new/as-built condition left (Ram et al. 2023).

- The SLR measures the rate of change of the backlog over time compared to the replacement value of the pavement work (Ram et al. 2023).

Proposed Transportation Asset Management Methodology

The cross-asset methodology proposed by this study is promising because it is relatively easy to use a separate tradeoff analysis tool specialized for cross-asset use cases that obtains its data from existing management systems. This research project documents one way that the cross-asset tradeoff analysis can be done and demonstrates the analysis using easily accessible tools. With few exceptions, the methodology relies on data already collected, generated, or soon-to-be-supported by these existing systems, including the Federal condition measures *(*percent Good and percent Poor) defined in 23 CFR 490 (CFR 2016a).

These management systems need certain additional data to make the methodology complete, data that the current management systems do not currently produce. These data include the following:

- Ten-year forecasts of asset-level Good and Poor conditions that are sensitive to treatment selection. Some management systems already have condition forecasting, especially for

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[28] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.

[29] Sadasivam and Mallela. *Identification of Effective. . .Vol. I: Pavement Performance Measures*.

bridges at the element level. What is needed is the less-detailed forecast of Good and Poor condition, which might be derived from element-level forecasts, as is done in StruPlan.

- Standardized performance measures for safety and mobility (and possibly environmental sustainability) that are at the same level of detail as the Federal condition measures. In the TA-MAPO tool, the suggested measures estimate the percent of assets that satisfy a set of LOS standards (i.e., *%Sufficient*). The proposed tradeoff analysis can function without these outcome measures, as was done in the three pilot studies for pavements (FHWA 2024b). However, the use of such measures will make the methodology more complete and enhance an agency's ability to develop programs that lead to the achievement of more of the Federal goals defined in 23 USC 150(b) and similar State goals (CFR 2021a).

- Vital prioritization measure for enablement of fair comparison among investment candidates from multiple classes of assets. This type of measure will need to incorporate the most significant aspects of performance—condition, safety, and mobility at a minimum—and support intertemporal tradeoffs using LCCA so that the effects of delayed work are fully recognized without being biased by the differing lifespans and technologies of different asset classes.

Chapter 3 of this report discussed the requirements of the outcome and prioritization measures, proposing the use of BCR as the primary means of setting priorities and allocating resources among asset classes. BCR relies on two important features of management systems, as follows:

- LCCA: Generates a long-time series of condition forecasts, agency corrective actions, and their costs and summarizes the NPV of costs, which is sensitive to near-term investment choices, especially for preservation and rehabilitation.

- User cost model: Quantifies the cost to the public of functional deficiencies in the network infrastructure affecting safety and mobility. This feature may also include nonuser costs, such as those due to pollution and climate change. It should include costs associated with the risk of transportation service disruption due to extreme events or advanced deterioration. Here, the significant costs are those that depend on near-term investment choices by the agency. Often, only the marginal or avoidable cost is estimated.

According to 23 CFR 515, consideration of whole life cost is a mandatory capability (CFR 2021b). However, none of the pilot agencies had this full capability in their PMSs. This limitation was a significant barrier to pilot testing, which was partially overcome by the post-processing of a large number of separate analyses. The BMSs in the pilot agencies have mature LCCA functionality but were unable to output the results in a form suitable for network-level analysis. This constraint was also a barrier, which was overcome by using a readily available open-source analysis tool (StruPlan) that was able to produce the needed outputs using BMS data (Thompson 2021).

This report discusses the RSI approach to pavement management analysis, which is similar to the approach commonly used in bridge management in its reliance on LCCA. BMS computations are more complex than PMS computations because of the multilevel hierarchy of bridges, elements, and protective elements, whose conditions interact. However, StruPlan demonstrates that these computations are feasible using suitable algorithms and multithreaded execution in a common spreadsheet program. For the pilot agencies, complete StruPlan scenarios required less than 2 min to generate all the data required (Thompson 2021).

User cost models were originally developed for PMSs, most significantly in the World Bank's HDM, which is still widely used in developing countries (Archondo-Callao 2008). These models were adopted and further developed in HERS and NBIAS as a means of representing safety and mobility benefits of projects in an asset-generic way (FHWA 2005; Cambridge Systematics 2011).[30] Similar models were used by most State DOTs starting in 1992, but they have been supported less since then, especially in the newest AASHTO BMS. These models are simple and could readily be incorporated into management systems. Their economic parameters are standardized and periodically updated in the AASHTO Red Book (AASHTO 2010).

Chapter 4 and appendix I of this report discuss the TA-MAPO tool, a prototype that was developed in the present study to demonstrate and test the proposed methodology. The algorithm used in the TA-MAPO tool is a simple multiyear budget-constrained prioritization, a model that is common in management systems. The tool uses the proposed outcome and prioritization measures to investigate 10-year performance targets, funding constraints, and funding allocations among different parts of an infrastructure network (FHWA 2024b).

The research team pilot tested the TA-MAPO tool using data contributed by the three pilot agencies. The tool worked well for this application, but its abilities were limited by the inability of agency management systems to conduct and output LCCA and user cost analyses for work candidates. Therefore, the research team had to conduct temporary processes to adapt the management system outputs to this application; these processes are described in appendix E. Chapter 9 outlined suggested enhancements to advance the functionality of asset management systems (including pavement management). Implementing these enhancements will enable agencies to overcome the challenges encountered during the pilot studies and make implementing the NGPPMs and TAMM a reality.

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[30] FHWA. 1999–2024. *NBIAS* investment analysis tool (software).

APPENDIX A. EVALUATION MATRICES FOR INITIAL STATE VALIDATION SELECTION ROUNDS

State 1 Evaluation Matrix

Table 26 through table 33 present interview questions provided to State 1 as part of the initial State agency selection process.

Table 26. Overall State 1 assessment.

Evaluation Criteria	Assessment
Sufficient resources for the effort.	Very Good. State 1 can dedicate a resource to the study and also has an ongoing contract with Boise State University's full-term data analyst and is hiring a second.
Management support for the effort.	Good. State 1 has monthly planning meetings and meets with executive management regularly. This effort can be added to meeting agendas easily.
Analysis capabilities for the methodology.	Very Good. State 1's PMS and BMS staff are open to changing their approach, and such ideas are typically well-received by leadership. The asset manager and key data analyst have been dabbling with the proposed process for years and will have support from the university.
PMS capabilities.	Good. PMS has most of the required inputs.
BMS capabilities.	Adequate. State 1 uses an inhouse designed system that is augmented by BrM (AASHTO 2023). Maintenance costs are not currently linked to asset condition.
Other capabilities for asset management systems.	Good. An enterprise asset system is integrated with the PMS.

Table 27. Assessment of State 1 data to support RSI analysis.

Data To Support RSI	Data Availability	Data Quality
Deterioration models for condition metrics (e.g., IRI, rutting, and cracking for pavements) (CFR 2017b).	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in pavement models and low confidence in bridge models; they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for IRI and rutting. Easily acceptable Federal measures that are predictable on a segment basis. Pavement treatment selection based on IRI and total cracking. However, State 1 is currently refining the selection process and treatment system forecasts. Bridge element, sub-element, scour, and seismic risk are used for treatment selection. Strategies are updated within every 10 years.	Adequate.
Yearly costs for the analysis period.	Very high confidence in recent collection and acceptable confidence in historic data for bridges and pavements. Construction history back to 1907. PMS cost data is updated annually. BMS cost data is updated within every 5 years. Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program. For pavements delivered by/in a maintenance work plan, costs will require a significant effort to provide.	Good.
Good/Fair/Poor condition assets for each year.	Very high confidence in recent collection and historic data.	Good.
Segment number/percent with treatment needs in the following categories: do-nothing, maintenance, preservation, rehabilitation, reconstruction (or other categories, as defined by agency).	For PCC and HMA maintenance, preservation, rehabilitation, and reconstruction, treatments have been defined and are updated within every 5 years. The PMS does not generate LCCs for each segment. High confidence in decision tree's ability to pick lowest LCC options.	Adequate.

G/F/P = Good/Fair/Poor; L&T = longitudinal and transverse; HMA = hot-mix asphalt.

Table 28. Assessment of State 1 data to support AUCR.

Data To Support AUCR	Data Availability	Data Quality
Deterioration models for condition.	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for IRI and rutting. Pavement treatment selection based on IRI and total cracking. (However, State 1 is currently refining the selection process and treatment system forecasts.) Bridge element, sub-element, scour, and seismic risk are used for treatment selection. Strategies are updated within every 10 years.	Adequate.
Yearly costs for segments in the network over the analysis period.	Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program. For pavements delivered by/in a maintenance work plan, costs will require a significant effort to provide. PMS does not generate LCCs for each segment. Federal measures can be predicted on a pavement-segment basis and are easily accessible.	Adequate.
LCCs for chosen analysis period.	High confidence in decision tree's ability to pick lowest LCC options. BMS used to generate LCC for work candidates and projects.	Good.
Data on programmed annual costs and actual annual costs at the network level for each asset (AUCR measure only).	Construction costs through a financial system that is integrated with the AMS. State 1 might face challenges getting accurate full project costs. State 1 is currently looking to integrate specific asset material and ROW costs.	Poor.
AUCR forecasting ability.	Adequate.	Adequate.

ROW = right of way.

Table 29. Assessment of State 1 data to support CAR.

Data To Support CAR	Data Availability	Data Quality
Condition performance models.	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for IRI and rutting. Federal measures can be predicted on a pavement-segment basis and are easily accessible. Pavement treatment selection is based on IRI and total cracking. (However, State 1 is currently refining the selection process and treatment system forecasts.) Bridge element, sub-element, scour, and seismic risk are used for treatment selection. Strategies are updated within every 10 years.	Adequate.
Yearly costs over the analysis period for the network segments.	Construction costs through a financial system that is integrated with the AMS. State 1 might face challenges getting accurate full project costs. State 1 is currently looking to integrate specific asset material and ROW costs.	Adequate.
Treatment histories.	Very high confidence in recent collection and acceptable confidence in historic data for bridges and pavements. Construction history dates back to 1907.	Very Good.
Optimized lifecycle strategy with policies for the analysis period.	PMS does not generate LCCs for each segment. High confidence in decision tree's ability to pick lowest LCC options.	Adequate.
CAR forecasting ability.	Good.	Adequate.

Table 30. Assessment of State 1 data to support ASI.

Data To Support ASI	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
Budget needs determined using the management system.	The current system works by allocating investments based on G/F/P conditions, mobilization, and safety benefits as well as State 1's other specific asset optimization practices. For pavements, the system is broken down by districts and by commerce and noncommerce routes.	Good.
Yearly allocations to address the needs determined through the agency's financial planning process that accounts for expected revenues, adjusted for inflation.	Unknown.	Unknown.
ASI forecasting ability.	Unknown.	Unknown.

Table 31. Assessment of State 1 data to support ASR.

Data To Support ASR	Data Availability	Data Quality
Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Unknown.	Unknown.
Asset value depreciation.	Unknown.	Unknown.
ASR forecasting ability.	Unknown.	Unknown.

Table 32. Assessment of State 1 data to support ACR.

Data To Support ACR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking, 8 pavement deterioration curves, and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Unknown.	Unknown.
Asset value depreciation.	Unknown.	Unknown.
ACR forecasting ability.	Unknown.	Unknown.

Table 33. Assessment of State 1 data to support SLR.

Data To Support SLR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (wheelpath, alligator, block, longitudinal, transverse, fatigue, edge, reflection, total), patching and patch deterioration, potholes, rutting/shoving, bleeding/flushing. PCC: Blowups, faulting, corner breaks, L&T joint seal damage, L&T joint spalling, map cracking, scaling, pumping, popouts. State 1 has more than 5 years of data for all distresses but block cracking. State 1 has 8 pavement deterioration curves and a robust set of decision trees. Acceptable confidence in models (bridge and pavement); they were updated within the past 2 years. State 1 owns and operates an inertial profile van, which videos the pavement for every road in both directions every year. State 1 uses software algorithms in conjunction with visual confirmation to assess cracks in pavement surfaces.	Very Good.
Management system funding required to address the total needs identified	The current system works by allocating investments based on G/F/P conditions, mobilization, and safety benefits as well as by State 1's asset optimization practices. For pavements, the system is broken down by districts and by commerce and noncommerce routes.	Good.
Financial planning funding committed to address the total needs identified	Unknown.	Unknown.
SLR forecasting ability.	Unknown.	Unknown.

STATE 2 EVALUATION MATRIX

Table 34 through table 41 present interview questions provided to State 2 as part of the initial State agency selection process.

Table 34. Overall State 2 assessment.

Evaluation Criteria	Assessment
Sufficient resources for the effort.	Adequate. Bridge and pavement staff are generally tied up and shorthanded; however, support will be provided if tool benefits are showcased convincingly.
Management support for the effort.	Poor. State 2 is unsure of its ability to support this effort well, especially as it acquires a new secretary and governor.
Analysis capabilities for the methodology.	Poor. State 2 finds it difficult to perform accurate LCCAs due to cost fluctuations.
PMS capabilities.	Good. State 2 uses a State-developed PMS.
BMS capabilities.	Good. BrM with preservation, rehabilitation, and replacement treatments and unit costs for bridge elements. BrM currently being updated to remove server data loading issues (AASHTO 2023). State 2 is unsure of its current ability to provide State bridge runs.
Other capabilities for asset management systems.	Adequate. State 2 desires to include other assets in the future (e.g., vehicle fleet and building management). Tradeoffs are currently made at the budget-setting level.

Table 35. Assessment of State 2 data to support RSI analysis.

Data To Support RSI	Data Availability	Data Quality
Deterioration models for condition metrics (e.g., IRI, rutting, and cracking for pavements) (CFR 2017b).	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
Treatment strategies.	More than 50-percent coverage in pavement structure data. Predictive capabilities for all distresses but longitudinal, fatigue, and reflection cracking. Federal measures can be predicted on a pavement-segment basis, but they require a significant effort to provide. Pavement treatment selection is based on IRI; transverse, durability, and total cracking; rutting; and faulting. Bridge element data is used for treatment selection.	Good.
Yearly costs for the analysis period.	Acceptable confidence in recent collection and historic data for pavements; high confidence in bridge data. PMS cost data is updated annually. Bridges and pavements: Specific treatment cost data can be provided for maintenance work plan, capital contract (requires a significant effort to provide for pavements), capital program.	Adequate.
Good/Fair/Poor condition assets for each year.	Unknown.	Unknown.
Segment number/percent with treatment needs in the following categories: do-nothing, maintenance, preservation, rehabilitation, reconstruction (or other categories, as defined by agency).	For PCC and HMA maintenance, preservation, rehabilitation, and reconstruction, treatments have been defined and are updated within every 10 years. The PMS generates LCCs for each segment but requires significant effort to generate them. The BMS does not. High confidence in decision tree’s ability to pick lowest LCC options. Not yet done for bridges.	Poor.

Table 36. Assessment of State 2 data to support AUCR.

Data To Support AUCR	Data Availability	Data Quality
Deterioration models for condition.	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
Treatment strategies.	More than 50-percent coverage in pavement structure data. Predictive capabilities for all distresses but longitudinal, fatigue, and reflection cracking. Federal measures can be predicted on a pavement-segment basis, but they require a significant effort to provide. Pavement treatment selection is based on IRI; transverse, durability, and total cracking; rutting; and faulting. Bridge element data is used for treatment selection.	Good.
Yearly costs for segments in the network over the analysis period.	Links are mostly in place between the agency project management system (projects with planning and actual costs) and PMS (segments with project numbers, annual condition).	Adequate.
LCCs for chosen analysis period.	The PMS generates LCCs for each segment but requires significant effort to generate them. The BMS does not. High confidence in decision tree's ability to pick lowest LCC options. Not yet done for bridges.	Adequate.
Data on programmed annual costs and actual annual costs at the network level for each asset (AUCR measure only).	State 2 acknowledges that keeping costs well-aligned with their associated asset may require additional tools and/or setups.	Adequate.
AUCR forecasting ability.	Adequate.	Adequate.

Table 37. Assessment of State 2 data to support CAR.

Data To Support CAR	Data Availability	Data Quality
Condition performance models.	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
Treatment strategies.	More than 50-percent coverage in pavement structure data. Predictive capabilities for all distresses but longitudinal, fatigue, and reflection cracking. Federal measures can be predicted on a pavement-segment basis, but they require a significant effort to provide. Pavement treatment selection is based on IRI; transverse, durability, and total cracking; rutting; and faulting. Bridge element data is used for treatment selection.	Good.
Yearly costs over the analysis period for the network segments.	Mobilization and traffic maintenance costs make it difficult for State 2 to separate pavement costs from project costs. Sometimes bridge costs are included in pavement projects, so cost separation is difficult.	Poor.
Treatment histories.	Routine maintenance (State force patching, chip seal, crack seal) is extremely limited. Contract maintenance (chip seal, patching) is approximately \$6 million per year. Contract maintenance is captured in the PMS. State 2 maintenance team works hard to capture in the PMS. Capital program (reconstruction) is 30 mi/yr or less. Substantial maintenance (anything not reconstruction or routine) is 1,200 mi/yr. These items are captured in the PMS.	Good.
Optimized lifecycle strategy with policies for analysis period.	A prioritization formula is used to produce bridge and pavement capital projects. The asset management team at the agency then uses the prioritized list of projects to identify those projects with imminent needs.	Adequate.
CAR forecasting ability.	Good.	Good.

Table 38. Assessment of State 2 data to support ASI.

Data To Support ASI	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
Budget needs determined using the management system.	For pavement projects, State 2 prioritized highest needs projects and determined what sections could and could not be fixed due to funding. Pavement project breakdown is 50-percent pavement decisionmaking based on condition, 30-percent capacity, and 20-percent modernization. Bridge programs are built asset by asset. Almost all the prioritization is based on existing bridge conditions. Capital projects do not come directly from the PMS or BMS. The PMS optimizes project selection after a worst-first selection.	Very Good.
Yearly allocations to address the needs determined through the agency's financial planning process that accounts for expected revenues, adjusted for inflation.	State 2 automatically inflates performance in its current process. State 2 hopes measures like ASR and ASI can help refine the process.	Good.
ASI forecasting ability.	Good.	Good.

Table 39. Assessment of State 2 data to support ASR.

Data To Support ASR	Data Availability	Data Quality
Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	For pavement projects, State 2 prioritizes highest-need projects and determines the sections that can be fixed and those that cannot be fixed due to exhausted funds.	Adequate.
Asset value depreciation.	Unknown.	Unknown.
ASR forecasting ability.	Unknown.	Unknown.

Table 40. Assessment of State 2 data to support ACR.

Data To Support ACR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	For pavement projects, State 2 prioritizes highest-need projects and determines the sections that can be fixed and those that cannot be fixed due to exhausted funds.	Adequate.
Asset value depreciation.	Unknown.	Unknown.
ACR forecasting ability.	Unknown.	Unknown.

Table 41. Assessment of State 2 data to support SLR.

Data To Support SLR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (block, longitudinal, transverse, fatigue, reflection), rutting/shoving. PCC: Faulting, durability cracking. 5 years of data for all distresses. Acceptable confidence in models (bridge and pavement); they were updated more than 10 years ago.	Good.
Management system funding required to address the total needs identified.	For pavement projects, State 2 prioritizes highest-need projects and determines the sections that can be fixed and those that cannot be fixed due to exhausted funds. Capital projects do not come directly from the PMS or BMS. The PMS optimizes project selection after a worst-first selection.	Adequate.
Financial planning funding committed to address the total needs identified.	The current State 2 funding process may require several changes to effectively calculate NGPPMs. Pavement project breakdown is 50-percent pavement decisionmaking based on condition, 30-percent capacity, and 20-percent modernization. State 2 has a good hold on project cost data and data needs, as it has the flexibility of establishing refined scopes.	Very Good.
SLR forecasting ability.	Good.	Good.

STATE 3 EVALUATION MATRIX

Table 42 through table 49 present interview questions provided to State 3 as part of the initial State agency selection process.

Table 42. Overall State 3 assessment.

Evaluation Criteria	Assessment
Sufficient resources for the effort.	Good. Only concern is turnaround time.
Management support for the effort.	State 3 is well-staffed.
Analysis capabilities for the methodology.	Adequate, but both the PMS and the BMS may face challenges at the project level.
PMS capabilities.	Adequate. The project level requires district and regional involvement.
BMS capabilities.	BrM with maintenance, PR&R treatments, and unit costs defined for each bridge element (AASHTO 2023). Supported by in-house reporting tool and spreadsheet.
Other capabilities for asset management systems.	N/A; State 3 desires to include other assets in the future.

PR&R = preservation, rehabilitation, and replacement.

Table 43. Assessment of State 3 data to support RSI analysis.

Data To Support RSI	Data Availability	Data Quality
Deterioration models for condition metrics (e.g., IRI, rutting, and cracking for pavements) (CFR 2017b).	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Federal measures cannot be predicted on a pavement-segment basis. Strategies are updated within every 10 years. Bridge scour risk is used for treatment selection.	Adequate.
Yearly costs for the analysis period.	High confidence in recent collection and historic data for bridges and pavements. PMS cost data is updated annually. Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program.	Very Good.
Good/Fair/Poor conditions assets for each year.	High confidence in recent collection and historic data.	Good.
Segment number/percent with treatment needs in the following categories: do-nothing, maintenance, preservation, rehabilitation, reconstruction (or other categories, as defined by agency).	According to the TAMP, State 3 has preservation treatments. However, they only have defined reconstruction treatments, according to the survey. PMS updates LCCs for each segment, and the data is easily accessible. High confidence in decision tree's ability to pick lowest LCC options. Not yet done for bridges.	Poor.

Table 44. Assessment of State 3 data to support AUCR.

Data To Support AUCR	Data Availability	Data Quality
Deterioration models for condition.	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Federal measures cannot be predicted on a pavement-segment basis. Strategies are updated within every 10 years. Bridge scour risk is used for treatment selection.	Poor.
Yearly costs for segments in the network over the analysis period.	High confidence in recent collection and historic data for bridges and pavements. PMS cost data is updated annually. Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program.	Very Good.
LCCs for chosen analysis period.	High confidence in decision tree's ability to pick lowest LCC options. Not yet done for bridges.	Adequate.
Data on programmed annual costs and actual annual costs at the network level for each asset (AUCR measure only).	PMS cost data is updated annually.	Unknown.
AUCR forecasting ability.	Good.	Adequate.

Table 45. Assessment of State 3 data to support CAR.

Data To Support CAR	Data Availability	Data Quality
Condition performance models.	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Federal measures cannot be predicted on a pavement-segment basis. Strategies are updated within every 10 years. Bridge scour risk is used for treatment selection.	Adequate.
Yearly costs over the analysis period for the network segments.	PMS cost data is updated annually.	Adequate.
Treatment histories.	High confidence in recent collection and historic data for bridges and pavements.	Good.
Optimized lifecycle strategy with policies for the analysis period.	High confidence in decision tree's ability to pick lowest LCC options. Not yet done for bridges.	Adequate.
CAR forecasting ability.	Good.	Adequate.

Table 46. Assessment of State 3 data to support ASI.

Data To Support ASI	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs (assumed to be available from management systems).	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
Budget needs determined using the management system.	Cost tables are within the LCCA. Cost data is collected by work type codes and cost tables. Process is updated annually.	Poor.
Yearly allocations to address the needs determined through the agency's financial planning process that accounts for expected revenues, adjusted for inflation.	State 3 has a statewide process for determining the appropriate allocation of funds by work type.	Adequate.
ASI forecasting ability.	State 3 has project-level investment data and network-level needs.	Good.

Table 47. Assessment of State 3 data to support ASR.

Data To Support ASR	Data Availability	Data Quality
Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program.	Adequate.
Asset value depreciation	Based on information from the interview, State 3 should be able to calculate asset value depreciation at a network level.	Adequate.
ASR forecasting ability.	State 3 has project-level investment data and network-level needs.	Adequate.

Table 48. Assessment of State 3 data to support ACR.

Data To Support ACR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program.	Adequate.
Asset value depreciation.	See ASR.	Adequate.
ACR forecasting ability.	State 3 has project-level investment data and network-level needs.	Adequate.

Table 49. Assessment of State 3 data to support SLR.

Data To Support SLR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	AC: Cracking (wheelpath, alligator, longitudinal, transverse, fatigue, block, edge, reflection), rutting, bleeding/flushing. IRI and another ride index. PCC: Faulting, map cracking, popouts. High confidence in models; they were updated within the past 2 years.	Good.
Management system funding required to address the total needs identified.	Bridges and pavements: Specific treatment cost data can be provided for planned actions, maintenance work plan, capital contract, capital program.	Adequate.
Financial planning funding committed to address the total needs identified.	Cost tables are within the LCCA. Cost data is collected by work type codes and cost tables. Process is updated annually.	Adequate.
SLR forecasting ability.	Adequate.	Adequate.

STATE 4 EVALUATION MATRIX

Table 50 through table 57 present interview questions provided to State 4 as part of the initial State agency selection process.

Table 50. Overall State 4 assessment.

Evaluation Criteria	Assessment
Sufficient resources for the effort.	Good. State 4 has a team with varied experience and is interested in the project.
Management support for the effort.	Good.
Analysis capabilities for the methodology.	Poor. Bridge LCC is done through in-house software, not a BMS. Management systems would require significant updates to be ready for the tradeoff tool.
PMS capabilities.	Adequate. The PMS is a tool created by a private company.
BMS capabilities.	Poor. State 4 uses an in-house system for analysis but does have the most recent version of BrM (AASHTO 2023). State 4 is unlikely to have the BMS configured and ready for use in this project effort. If needed, State 4 could use 2017 data rather than 2018 data to supply LCC information.
Other capabilities for asset management systems.	Adequate. State 4 has a license for an online decisionmaking software, but it is not used on the SHS. State 4 currently uses an in-built software for tradeoff analysis.

Table 51. Assessment of State 4 data to support RSI analysis.

Data To Support RSI	Data Availability	Data Quality
Deterioration models for condition metrics (e.g., IRI, rutting, and cracking for pavements) (CFR 2017b)..	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for all distresses but rutting. Federal measures can be predicted on a pavement-segment basis but require significant effort to provide. Pavement treatment selection is based on all distresses but patching. Bridge scour risk, NBI data (for work type logic), and then element data (for specific treatments, such as overlay, expansion joints, barriers, etc.) and sub-element data are used for treatment selection (FHWA 2023).	Good.
Yearly costs for the analysis period.	High confidence in recent collection and historic data for bridges and pavements. PMS cost data is updated within every 5 years. BMS cost data is updated annually. Pavements: Specific treatment cost data can be provided for planned actions, capital program. For pavements delivered by capital contract costs. All bridge-specific cost data are available (planned actions, capital program, maintenance, and capital contract).	Good.
Good/Fair/Poor condition assets for each year.	High confidence in recent collection and historic data.	Adequate.
Segment number/percent with treatment needs in the following categories: do-nothing, maintenance, preservation, rehabilitation, reconstruction (or other categories, as defined by agency).	For PCC and HMA maintenance, preservation, rehabilitation, and reconstruction, treatments have been defined and are updated within every 5 years. The PMS generates LCCs for each segment but requires significant effort to generate them. The BMS does not. Acceptable confidence in the decision tree's ability to pick the lowest LCC options.	Adequate.

Table 52. Assessment of State 4 data to support AUCR.

Data To Support AUCR	Data Availability	Data Quality
Deterioration models for condition.	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for all distresses but rutting. Federal measures can be predicted on a pavement-segment basis but require significant effort to provide. Pavement treatment selection based on all distresses but patching. Bridge scour risk, NBI data (for work type logic) (FHWA 2023). Element data (for specific treatments, such as overlay, expansion joints, barriers, etc.) and sub-element data are used for treatment selection.	Good.
Yearly costs for segments in the network over the analysis period.	PMS cost data is updated within every 5 years. BMS cost data is updated annually. Pavements: Specific treatment cost data can be provided for planned actions, capital program. For pavements delivered by capital contract costs. All bridge-specific cost data are available (planned, capital program, maintenance, and capital contract).	Adequate.
LCCs for chosen analysis period.	The PMS generates LCCs for each segment but requires significant effort to generate them. The BMS does not. Acceptable confidence in decision tree's ability to pick lowest LCC options.	Adequate.
Data on programmed annual costs and actual annual costs at the network level for each asset (AUCR measure only).	Neither bridges nor pavements track comparisons between projected and actual project costs.	Poor.
AUCR forecasting ability.	Adequate.	Adequate.

Table 53. Assessment of State 4 data to support CAR.

Data To Support CAR	Data Availability	Data Quality
Condition performance models.	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Treatment strategies.	Project-specific pavement structure data. Predictive capabilities for all distresses but rutting. Federal measures can be predicted on a pavement-segment basis but require significant effort to provide. Pavement treatment selection based on all distresses but patching. Bridge scour risk, NBI data (for work type logic) (FHWA 2023). Element data (for specific treatments, such as overlay, expansion joints, barriers, etc.) and sub-element data are used for treatment selection.	Good.
Yearly costs over the analysis period for the network segments.	PMS cost data is updated within every 5 years. BMS cost data is updated annually. Pavements: Specific treatment cost data can be provided for planned actions, capital program. For pavements, delivered by capital contract costs. All bridge-specific cost data are available (planned, capital program, maintenance, and capital contract).	Adequate.
Treatment histories.	High confidence in recent collection and historic data for bridges and pavements.	Good.
Optimized lifecycle strategy with policies for the analysis period.	The PMS generates LCCs for each segment but requires significant effort to generate them. The BMS does not. Acceptable confidence in decision tree’s ability to pick lowest LCC options.	Adequate.
CAR forecasting ability.	Good.	Good.

Table 54. Assessment of State 4 data to support ASI.

Data To Support ASI	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Budget needs determined using the management system.	Not effectively tracked.	Poor.
Yearly allocations to address the needs determined through the agency's financial planning process that accounts for expected revenues adjusted for inflation.	Unknown.	Unknown.
ASI forecasting ability.	Unknown.	Unknown.

Table 55. Assessment of State 4 data to support ASR.

Data To Support ASR	Data Availability	Data Quality
Condition performance models, treatment strategies, and treatment costs (assumed to be available from management systems).	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Bridge unit costs developed for maintenance, preservation, rehabilitation, and reconstruction.	Adequate.
Asset value depreciation.	Unknown.	Unknown.
ASR forecasting ability.	Unknown.	Unknown.

Table 56. Assessment of State 4 data to support ACR.

Data To Support ACR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. More than 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
CRV: Unit costs for asset replacement from the agency's existing management systems can be leveraged.	Bridge unit costs developed for maintenance, preservation, rehabilitation, and reconstruction.	Adequate.
Asset value depreciation.	Unknown.	Unknown.
ACR forecasting ability.	Unknown.	Unknown.

Table 57. Assessment of State 4 data to support SLR.

Data To Support SLR	Data Availability	Data Quality
Condition deterioration models, treatment strategies, and treatment costs.	IRI. AC: Cracking (wheelpath, alligator, longitudinal, transverse, edge), patching, rutting, raveling. PCC: Faulting, transverse joint spalling, durability cracking, cracked and broken panels. 5 years of data for all distresses. High confidence in pavement models and acceptable confidence in bridge models; they were updated within the past 2 years.	Good.
Management system funding required to address the total needs identified.	State 4 makes no clear distinction between contract maintenance and maintenance crew repairs for pavements and bridges.	Poor.
Financial planning funding committed to address the total needs identified.	Unknown.	Unknown.
SLR forecasting ability.	Unknown.	Unknown.

APPENDIX B. SUPPLEMENTAL DATA FOR IDAHO VALIDATION

The approaches and methodology described in chapter 5 for validating the NGPPMs and proposed TAMM required the research team to perform data mapping. Table 58 and table 59 summarize the data fields that were needed for the validation and how these fields were mapped to the ITD PMS data output fields.

Table 60 outlines the process that was followed for mapping the ITD treatment work types to the FHWA work types to ensure that the treatment categories considered in the validation efforts are generic and can be used across all agencies.

Table 58. ITD data sources and fields mapped to each data element used in NGPPM calculations.

Field(s)	Definition	Data Element	Data Source(s)
PMS section number	An identifier the agency uses to relate the data to the PMS.	Segment ID	PMS output file
Beginning milepost	The start of the PMS segment.	Segment ID	PMS output file
Ending milepost	The end of the PMS segment.	Segment ID	PMS output file
Direction	Delineates whether the mile points are increasing or decreasing along the travel direction.	Segment ID	PMS output file
Total lane-miles	Lane-miles = (ending milepost – beginning milepost) × number of lanes.	Segment ID	PMS output file
Plan year	Identifies the year in the analysis period.	Segment ID	PMS output file
Functional class	Highway system the pavement segment belongs to.	Functional class	PMS output file
AADT (bidirectional)	Total vehicle traffic in a year divided by 365 d.	Traffic	PMS output file
Broad pavement type	Flexible and rigid pavements.	Pavement type	PMS output file
Condition indices (SDI, NDI, OCI, slab index, and joint index)	Resulting segment conditions in each year of the analysis.	ITD performance measures	PMS output file
Faulting, rutting	Indicates when a segment is in Good, Fair, or Poor condition.	ITD LOS thresholds	PMS configuration document
Strategy type, treatment, treatment cost	Describes a set of inputs to the PMS that establish the constraints of a specific strategy.	Lifecycle treatment strategies	PMS output file
Treatment cost	Sum of treatment costs by treatment category in the optimal strategy.	Budget needs (allotted and backlog)	PMS output file
Pavement type, SDI/OCI, treatment, treatment cost	Condition-based depreciation based on feasible treatments within OCI condition ranges.	Annual and cumulative asset value depreciation	PMS output file, PMS configuration document
Pavement type, treatment, and treatment cost	Replacement value.	Current asset replacement value	PMS output file, PMS configuration document
Pavement type, SDI/OCI, treatment and treatment cost	Replacement value less condition-based depreciation.	Current DRV	PMS output file, PMS configuration document

Table 59. ITD pavement data sources and fields mapped to each data element used in proposed TAMM calculations.

Field(s)	Definition	Data Element	Data Source(s)
PMS section number, BMP, EMP, direction, total lane-miles, plan year	An identifier the agency uses to relate the data to the PMS.	Segment ID	PMS output file
FA system type	Is the asset included within the NHS for the TAMP?	NHS	PMS output file
Functional class	Is the asset included on the Interstate system for Federal performance management regulations?	Interstate	PMS output file
State highway system	Is the asset on the SHS (i.e., maintained by the State DOT)?	SHS	PMS output file
Maintenance district	Can be any relevant administrative subdivision of the highway network.	District	PMS output file
Total lane-miles	Lane-miles = (EMP−BMP) × number of lanes.	Size	PMS output file
Pavement type, treatment, treatment cost	The cost to reconstruct the asset segment.	Replacement value	PMS output file
AADT (bidirectional)	Total vehicle traffic in a year divided by 365 d.	Utilization	PMS output file
MAP-21 faulting RWP average, MAP-21 rutting average (U.S. Congress 2012)	Condition measure weighted by size following Federal performance management rule.	Federal-based performance measures	PMS output file
Assumed to be 100	*%Sufficient*, according to LOS standard. Indicates whether the asset satisfies applicable LOS standards related to safety, which may differ among asset classes (FHWA 2024b).	Safety	—
Assumed to be 100	*%Sufficient*, according to LOS standard. Indicates whether the asset satisfies applicable LOS standards related to mobility, which may differ among asset classes (FHWA 2024b).	Mobility	—
Treatment cost	Sum of treatment costs by treatment category in the PMS strategy runs.	Budget needs	PMS output file
Treatment, treatment cost	Treatments and costs recommended within the PMS strategy runs.	Treatment category and cost	PMS output file
Treatment, treatment cost, condition index	Savings achieved by deferring a treatment.	Long-term agency savings	PMS output file
Assumed to be 0	Difference in user costs between the options of treatment and no treatment.	User savings	—

—No data.

BMP = beginning milepost; FA = Federal aid; EMP = ending milepost; RWP = right wheel path.

Table 60. Treatments mapped from ITD treatments to FHWA work types.

ITD Treatment	ITD Treatment Category	FHWA Work Type
Blank Field/Cell	Do Nothing	Do Nothing
Preservation—Flexible	Preservation	Maintenance
Preservation—Rigid	Preservation	Preservation
Resurfacing—Flexible	Resurfacing	Preservation
Restoration—Flexible	Restoration	Rehabilitation
Restoration—Rigid	Restoration	Rehabilitation
Rehabilitation—Flexible	Rehabilitation	Rehabilitation
Rehabilitation—Rigid	Rehabilitation	Rehabilitation
Reconstruction—Flexible	Reconstruction	Reconstruction
Reconstruction—Rigid	Reconstruction	Reconstruction

APPENDIX C. SUPPLEMENTAL DATA FOR SOUTH DAKOTA VALIDATION

The approaches and methodology described in chapter 6 for validating the NGPPMs and proposed TAMM required the research team to perform data mapping. Table 61 and table 62 summarize the pavement data fields that were needed for the validation and how they were mapped to the data fields within the PMS data output.

Table 63 outlines the mapping process followed by the research team to map the SDDOT treatment work types to the FHWA work types, so as to ensure that the treatment categories considered in the validation efforts are generic can be used across all agencies.

Table 61. SDDOT data sources and fields mapped to each pavement data element used in NGPPM calculations.

Field(s)	Definition	Data Element	Data Source(s)
Name	An identifier the agency uses for the PMS segment.	Segment ID	PMS output file
Length	Length of the PMS segment along the centerline.	Length	PMS output file
DTIMS_DATA__NO_LANES	Total number of lanes in a segment.	Number of lanes	PMS output file
dav_PAVETYPE	An identifier the agency uses to identify the PMS segment type.	Pavement Category	PMS output file
aav_CMP (SCI), BC (Benefit-to-Cost ratio)	Resulting segment condition in each year of the analysis.	SDDOT performance measures	PMS output file
aav_RUFF (Roughness), aav_CMP	Indicates when a segment is in Good, Fair, or Poor condition.	SDDOT LOS thresholds	SDDOT 2019 TAMP document
Strategy_Key, treatments, treatment costs	Describes a set of inputs to the PMS that establish the constraints to a specific strategy.	Lifecycle treatment strategies	PMS output file
Treatment costs	Sum of total treatment costs associated with nonoptimal strategy.	Budget allocated to address needs	PMS output file
dav_PAVETYPE, aav_CMP, treatment, treatment cost	Condition-based depreciation based on feasible treatments within SCI condition ranges.	Annual and cumulative asset value depreciation	PMS output file, SDDOT 2020 Synopsis
dav_PAVETYPE, aav_CMP, treatment, treatment cost	Replacement value.	Current asset replacement value	PMS output file, SDDOT 2020 Synopsis
dav_PAVETYPE, aav_CMP, treatment, PVCost	Replacement value less condition-based depreciation.	Current DRV	PMS output file, SDDOT 2020 Synopsis

Table 62. SDDOT data sources and fields mapped to each pavement data element used in proposed TAMM validation.

Field(s)	Definition	Data Element	Data Source(s)
Name	An identifier the agency uses to relate the data to the PMS.	Segment ID	PMS output file
NEEDS_BOOK_ FUNC_CLASS	Is the asset included within the NHS for the TAMP?	NHS	PMS output file
NEEDS_BOOK_ FUNC_CLASS	Is the asset included on the interstate system for Federal performance management regulations?	Interstate	PMS output file
SHS	Is the asset on the SHS (i.e., maintained by the State DOT)?	SHS	PMS output file
DTIMS_DATA_REGION	Can be any relevant administrative subdivision of the highway network.	District	PMS output file
DTIMS_DATA_NO_LANES, Length	Total lane-miles = length × number of lanes.	Size	PMS output file
dav_PAVETYPE, treatment, treatment cost	The cost to reconstruct the asset segment.	Replacement value	PMS output file
aav_CMP	Condition measure weighted by size following Federal National Performance Management Measures final rule (Office of the Federal Register 2017).	Federal-based performance measures	PMS output file
Assumed to be 100	*%Sufficient*, according to LOS standards. Indicates whether the asset satisfies applicable LOS standards related to safety, which may differ among asset classes (FHWA 2024b).	Safety	N/A
Assumed to be 100	*%Sufficient*, according to LOS standards. Indicates whether the asset satisfies applicable LOS standards related to mobility, which may differ among asset classes (FHWA 2024b).	Mobility	N/A
Treatment costs	Sum of treatment costs by treatment category in the PMS strategy runs.	Budget needs	PMS output file
Treatment, treatment cost	Treatments and costs recommended within the PMS strategy runs.	Treatment category and cost	PMS output file
Treatment, treatment cost, SCI	Savings achieved by deferring a treatment.	Long-term agency savings	PMS output file
Assumed to be 0	Difference in user costs between the options of treatment and no treatment.	User savings	N/A

Table 63. Treatments from SDDOT treatment categories mapped to FHWA work types.

SDDOT Treatment	SDDOT Treatment Category	FHWA Work Type
Blank Field/Cell	Do Nothing	Do Nothing
Routine Pavement Maintenance	Highway Preservation	Maintenance
AC Resurfacing	Highway Preservation	Preservation
Pavement Restoration	Highway Preservation	Preservation
Blotter Surfacing	Highway Preservation	Preservation
Joint Repair	Highway Preservation	Preservation
Mill	Highway Preservation	Preservation
Pavement Grinding	Highway Preservation	Preservation
Rout and Seal	Highway Preservation	Preservation
Rout and Seal	Highway Preservation	Preservation
Asphalt Surface treatment	Highway Preservation	Preservation
Gravel Resurfacing	Highway Preservation	Preservation
Dowel Bar Retrofit	Highway Preservation	Preservation
Micro-surfacing	Highway Preservation	Preservation
Cold In Place	Highway Rehabilitation	Rehabilitation
Rubblize Existing PCC/CRC	Highway Rehabilitation	Rehabilitation
PCCP Surfacing	Highway Rehabilitation	Rehabilitation
Crack & Seat	Highway Rehabilitation	Rehabilitation
AC Surfacing	Highway Reconstruction	Reconstruction
Ancillary Treatments	Highway Reconstruction	Reconstruction
Remove and Replace PCC Surfacing	Highway Reconstruction	Reconstruction
Reconstruct to PCC pavements	Highway Reconstruction	Reconstruction
Shoulder Widening	Highway Reconstruction	Reconstruction
Interim Surfacing	Highway Reconstruction	Reconstruction
Gravel Surfacing	Highway Reconstruction	Reconstruction

APPENDIX D. SUPPLEMENTAL DATA FOR TEXAS VALIDATION

The approaches and methodology described in chapter 7 for validating the NGPMs and TAMM required the research team to perform data mapping. Table 64 and table 65 summarize the pavement data fields needed for the validation and their mapping to the data fields within the PMS data output. Table 66 outlines the mapping process the research team followed for mapping the TxDOT's treatment work types to the FHWA work types to ensure that the treatment categories considered in the validation efforts are generic and can be used across all agencies.

Table 64. TxDOT data sources and fields mapped to each data element used in NGPPM calculations.

Field(s)	Definition	Data Element	Data Source(s)
PMS SECTION ID	Identifies the highway associated with a data collection section. This field includes the highway system, highway number, highway suffix, and roadbed ID.	Segment ID	PMS output file
DIRECTION	The primary direction of travel, in ascending reference marker order, for a section of highway.	Segment ID	PMS output file
SCENARIO YEAR	Identifies the year in the analysis period.	Segment ID	PMS output file
BEGINNING DFO	The start of the PMS segment.	Beginning mile point	PMS output file
ENDING DFO	The end of the PMS segment.	End mile point	PMS output file
NUMBER OF LANES	Total number of lanes in a segment.	Number of lanes	PMS output file
FUNCTIONAL-SYSTEM	Highway system the pavement segment belongs to.	Functional class	PMS output file
AADT CURRENT	Total annual vehicle traffic divided by 365 d.	Traffic (AADT)	PMS output file
BROAD PAVEMENT TYPE	An identifier the agency uses to identify the PMS segment type.	Pavement category	PMS output file
CONDITION SCORE	Resulting segment condition in each year of the analysis.	TxDOT performance measures	PMS output file
CONDITION SCORE CLASSIFICATION	Indicates how data collection sections fall within the range of score values.	TxDOT LOS thresholds	PMS output file
SIGNED HWY AND ROADBED ID, DIRECTION, BEGINNING DFO, TREATMENT COST, AADT CURRENT	Describes a set of inputs to the PMS that establish the constraints of a specific strategy.	Optimized lifecycle treatment strategy	PMS output file
SIGNED HWY AND ROADBED ID, DIRECTION, BEGINNING DFO, TREATMENT, TREATMENT COST, AADT CURRENT	Describes a set of inputs to the PMS that establish the constraints of a specific strategy.	Suboptimal lifecycle treatment strategies	PMS output file
	Sum of total treatment costs associated with optimal strategy.	Budget needs	PMS output file
TREATMENT COST	Sum of total treatment costs associated with nonoptimal strategy.	Budget allocated to address needs	PMS output file
BROAD PAVEMENT TYPE, CONDITION SCORE, TREATMENT, TREATMENT COST, AADT CURRENT	Condition-based depreciation based on feasible treatments within CS ranges.	Annual and cumulative asset value depreciation	PMS output file
BROAD PAVEMENT TYPE, TREATMENT COST	Replacement value less condition-based depreciation.	Current asset replacement value	PMS output file

Table 65. TxDOT data sources and fields mapped to each pavement data element used in TAMM validation.

Field(s)	Definition	Data Element	Data Source(s)
PMS SECTION ID, SCENARIO YEAR	An identifier the agency uses to relate the data to the PMS.	Segment ID	PMS output file
FUNCTIONAL CLASS	Is the asset included within the NHS for the TAMP?	NHS	PMS output file
FUNCTIONAL CLASS	Is the asset included on the Interstate system for the Federal performance management regulations?	Interstate	PMS output file
Assumed to be “Yes”	Is the asset on the SHS (i.e., maintained by the State DOT)?	SHS	PMS output file
SCENARIO	Can be any relevant administrative subdivision of the highway network.	District	PMS output file
LANE-MILES	Lane-miles = (end mile point − beginning mile point) × number of lanes.	Size	PMS output file
BROAD PAVEMENT TYPE, TREATMENT COST	Cost to reconstruct the asset segment.	Replacement Value	PMS output file
AADT CURRENT	Total vehicle traffic in a year divided by 365 d.	Utilization	PMS output file
CONDITION SCORE	Condition measure weighted by size following Federal performance management rule.	Federal-based performance measures	PMS output file
Assumed to be 100	*%Sufficient*, according to LOS standard. Indicates whether the asset satisfies applicable LOS standards related to safety, which may differ among asset classes (FHWA 2024b).	Safety	N/A
Assumed to be 100	*%Sufficient*, according to LOS standard. Indicates whether the asset satisfies applicable LOS standards related to mobility, which may differ among asset classes (FHWA 2024b).	Mobility	N/A
TREATMENT COST	Sum of treatment costs by treatment category in the PMS strategy runs.	Budget needs	PMS output file
TREATMENT, TREATMENT COST	Treatments and costs recommended within the PMS strategy runs.	Treatment category and cost	PMS output file
TREATMENT, TREATMENT COST, CONDITION SCORE, AADT CURRENT, BROAD PAVEMENT TYPE	Savings achieved by deferring a treatment.	Long-term agency savings	PMS output file
Assumed to be 0	Difference in user costs between the options of treatment and no treatment.	User savings	N/A

Table 66. TxDOT treatments and treatment levels mapped to FHWA work types.

TxDOT Treatment	TxDOT Treatment Level	FHWA Work Type
Seal coat	Preventive Maintenance	Preservation
Thin overlay, 2 inches thick or less	Preventive Maintenance	Preservation
Mill and inlay, 2 inches thick or less	Preventive Maintenance	Preservation
Hot in-place recycling	Preventive Maintenance	Preservation
Microsurfacing/slurry seal	Preventive Maintenance	Preservation
Scrub seal	Preventive Maintenance	Preservation
Overlay greater than 2 inches but less than 4 inches thick	Light Rehabilitation	Rehabilitation
Mill and inlay between 2 and 4 inches thick	Light Rehabilitation	Rehabilitation
Overlay between 4 and 6 inches thick	Medium Rehabilitation	Rehabilitation
Mill and inlay greater than 4 inches but less than 6 inches thick	Medium Rehabilitation	Rehabilitation
Whitetopping	Medium Rehabilitation	Rehabilitation
Overlays greater than 6 inches thick	Heavy Rehabilitation	Rehabilitation
Mill and inlay greater than 6 inches thick	Heavy Rehabilitation	Rehabilitation
Full reconstruction	Heavy Rehabilitation	Reconstruction
Full depth reclamation (pulverization and stabilization), new HMA surface	Heavy Rehabilitation	Rehabilitation
Full depth reclamation (pulverization and add new base), new seal coat surface	Heavy Rehabilitation	Rehabilitation
Half depth repair/full depth repair	Preventive Maintenance	Preservation
Diamond grinding and grooving	Preventive Maintenance	Preservation
Thin ACP overlays 2 inches thick or less	Preventive Maintenance	Preservation
ACP overlay greater than 2 inches and less than 4 inches thick	Light Rehabilitation	Rehabilitation
ACP overlay greater than 4 inches and less than 6 inches thick	Medium Rehabilitation	Rehabilitation
Reconstruction	Heavy Rehabilitation	Reconstruction
Rubblization & overlay greater than 6 inches thick	Heavy Rehabilitation	Rehabilitation
Bonded concrete overlay	Heavy Rehabilitation	Rehabilitation
Unbonded concrete overlay	Heavy Rehabilitation	Rehabilitation
Joint and/or crack sealing	Preventive Maintenance	Preservation
Half depth repair	Preventive Maintenance	Preservation
Slab replacement	Preventive Maintenance	Preservation
ACP overlay greater than 2 inches but less than 4 inches thick	Light Rehabilitation	Rehabilitation
Dowel bar retrofit and grinding	Light Rehabilitation	Rehabilitation
ACP overlay greater than 4 inches but less than 6 inches thick	Medium Rehabilitation	Rehabilitation
Rubblizing and ACP resurfacing greater than 6 inches thick	Heavy Rehabilitation	Rehabilitation

ACP = asphalt concrete pavement.

APPENDIX E. COMPATIBLE PERFORMANCE COMPUTATIONS IN MANAGEMENT SYSTEMS

The proposed TAMM discussed in this report features a cross-asset tradeoff analysis that decomposes relevant decisions into two programming stages within a program horizon, which is typically 10 years. Within that program, horizon decisions are revisited and subject to change on a regular cycle, usually every year or (in a few agencies) every biennium. The two stages are as follows:

- Scoping stage: In any one given program year, conditions are observed or forecast for the beginning of the year on every asset, and decision rules determine what treatments will be considered in response to these conditions. For each considered treatment, a long-term activity profile is generated, and long-term social cost is computed as the NPV of a long stream of agency, user, and nonuser costs. This long stream includes the treatment under consideration and extends beyond the lifespan of the asset currently in place. All agency costs, such as annual routine maintenance and reconstruction costs, are included. The treatment with the lowest long-term social cost is selected. This calculation is done in a manner specific to each class of assets. For example, it may be done to produce a separate fiscally unconstrained listing of investment candidates for each program year for each class of assets in a PMS or BMS.
- Timing stage: In each program year, the selected investment candidates on all assets are prioritized using a BCR. The benefit (numerator) of each candidate is the avoidable excess long-term social cost if the decision must be delayed by 1 year because of funding constraints. The cost (denominator of the BCR) is the amount set aside from the budget constraint if the investment candidate is selected. If the candidate is selected, its long-term social cost is the amount computed in the scoping stage for the selected treatment in the considered program year. If the candidate is not selected, the decision is postponed to the following year, where the long-term social cost is assumed to be the amount computed for the selected treatment in the following year. The selected treatment in the following year is assumed to be the treatment that minimizes social costs in that year, which may be different from the treatment that minimizes social costs in the considered program year.

Operations researchers familiar with capital programming algorithms will recognize this tradeoff analysis as a “greedy algorithm,” as it gives priority to benefits recognized earlier in the program horizon in an attempt to accumulate benefits as quickly as possible. This algorithm is justified for the intended applications because uncertainty in funding constraints increases substantially for each year into the future, faster than other uncertainties covered by the discount rate. Agencies and stakeholders recognize the funding uncertainty and allow changes in programming decisions from year to year to adapt to the level of funding that actually becomes available. Agencies plan their preconstruction activities based on the program, as revised each year—often over-programming as a risk management measure to ensure that enough projects are “on the shelf” to use unanticipated increments of funding—and can tolerate delays due to unexpected shortages of funding.

Chapter 3 of this report provides a narrative description of the tradeoff analysis, including needs and expectations for the performance measures used in the model. Chapter 4 and appendix I describe a spreadsheet model used in three pilot studies as a demonstration of the methodology.

These chapters focus on the timing stage, assuming that external management systems provide the analysis and results of the scoping stage for each class of assets.

This appendix provides a more mathematical treatment, focusing on the scoping stage. It discusses possible ways to develop the long-term social cost and outcome forecasts, using as examples the methods developed in the three pilot studies. There are many ways of performing these calculations, which all represent forecasts of decisions and consequences that are many years in the future and therefore characterized by substantial uncertainty. The scientific evolution of management systems is oriented toward researching ways to make these forecasts as accurate as possible and validate and refine them over time as data are gathered and improved.

Provided that the management systems are regularly evaluated and improved with up-to-date methodologies and calibrated to real-life outcomes, it is valid for the mathematical methods to vary substantially among asset classes. Chapter 3 discusses areas where it is important for the different asset classes to remain consistent, especially the need to include all significant types of project benefits relevant to each asset class. The examples given in later sections of this appendix demonstrate ways that the methods might vary substantially.

In a mathematical form, the tradeoff analysis performance measure introduced in chapter 3 and computed in the TA-MAPO tool is computed as follows:

$$BCR_{ya} = \frac{LTSC_{(y+1)a} - LTSC_{ya}}{IC_{ya}} \tag{12}$$

Where:

BCR_{ya} = BCR of the investment candidate selected for asset a computed for program year y.

$LTSC_{(y+1)a}$ = long-term social cost of the investment candidate selected for asset a for program year $y + 1$.

$LTSC_{ya}$ = long-term social cost of the investment candidate selected for asset a for program year y.

IC_{ya} = initial cost of the investment candidate selected for asset a for program year y.

The numerator in equation 14 is the benefit, and the denominator is the cost, computed for each asset in the applicable management system. As discussed in chapter 3, the treatments are selected for every asset without regard to budget constraints. The assumption is made that no programmed work is done in any earlier year on the given asset, except for routine unprogrammed maintenance, such as pothole-filling, which may have been done. A separate list of investment candidates is generated for each program year.

Each long-term social cost represents a long-term stream of costs incurred by the agency, users, and nonusers, beginning in the indicated program year with the treatment selected for that year. The long-term social cost is represented by an NPV of the cost stream, discounted to the indicated year. Between year y and year $y + 1$, condition of the asset may change, resulting in increases in agency routine maintenance costs, increases in user costs related to safety and mobility, and increases in nonuser costs related to environmental sustainability. Decision rules for treatment selection are often based, in part, on condition, so the deterioration may change the selected treatment and the subsequent long-term cost stream. Each management system should estimate these costs to the extent they are relevant.

The calculation of routine maintenance, user, and nonuser costs is commonly simplified by removing them from the long-term cost stream and considering only the change in first-year costs that is caused by selecting the investment candidate in year *y*. In this case, the performance measure is computed as follows:

$$BCR_{ya} = \frac{LTPC_{(y+1)a} - LTPC_{ya} + MC_{ya} + UC_{ya}}{IC_{ya}} \tag{13}$$

Where:

BCR_{ya} = BCR of the investment candidate selected for asset *a* computed for program year *y*.
$LTPC_{(y+1)a}$ = long-term programmed agency cost of the investment candidate selected for asset *a* for program year $y + 1$.
$LTPC_{ya}$ = long-term programmed agency cost of the investment candidate selected for asset *a* for program year *y*.
MC_{ya} = savings in routine maintenance cost for asset *a* for program year *y*.
UC_{ya} = savings in user and nonuser cost for asset *a* for program year *y*.
IC_{ya} = initial cost of the investment candidate selected for asset *a* for program year *y*.

ESTIMATING AGENCY BENEFITS

The proposed methodology estimates the agency benefit for each asset (or investment unit) and program year (or period). The agency benefit is the savings in long-term agency costs if the treatment is done this year instead of waiting until the next year to decide. If the model form in equation 15 is used, agency benefit incorporates the combined term: $LTPC_{(y+1)a} - LTPC_{ya} + MC_{ya}$. The first two terms are each the NPV of a long-term series of costs, incorporating all anticipated activities other than routine maintenance, including first-year costs, if any. The third term is 1 year of routine maintenance costs, based on conditions forecast for the program year *y*.

Agency benefit is especially important for evaluating the level of investment in preservation. Preservation work often improves aspects of condition, such as pavement cracking or bridge paint condition, that are not experienced by road users and therefore do not produce user costs. The benefit of preservation work is to delay the need for more expensive treatments. The long-term agency benefit model ensures that this benefit of preservation is properly considered so that an appropriate allocation of resources can be made.

Management systems that have a long-range planning capability typically calculate a year-by-year forecast of future conditions for a given asset; each year, these systems use decision trees programmed into the software by the agency to decide whether to act and what action needs to be taken. If an action is taken, a cost is incurred, and condition is improved. The rate of subsequent deterioration may be affected. This process typically extends beyond the lifespan of the asset and includes reconstruction actions. Each cost is discounted to the program year when the choice of action is to be made. The length of the long-term cost analysis can vary but should be far enough into the future so that adding more years is unlikely to affect current decisions. The general equation for long-term programmed cost is:

$$LTPC_{ya} = \sum_{z=y}^{Z} \left(\frac{1}{1+d}\right)^{z-1} IC_{za} \tag{14}$$

Where:

$LTPC_{ya}$ = long-term programmed cost of the investment candidate considered or selected for asset a in program year y.

Z = number of years in the long-term cost analysis; usually greater than the normal lifespan of the asset. Z is the maximum value of forecast year z.

d = Real discount rate, not including inflation—the annual fraction that the value of a future cost is reduced by postponing the cost.

IC_{za} = Initial cost of a future activity selected for asset a for forecast year z.

Management systems typically generate multiple investment candidates for each asset in each program year y, including the possibility of taking no action. The alternative yielding the lowest value of long-term cost is selected. Usually, the actions selected for future years z are determined entirely by decision rules, but some systems may consider multiple alternatives for those future actions as well.

Discount rates have been observed, in practice, to frequently fall in the range of 1.8 to 2.5 percent. The long-range analysis period Z has been observed to vary from 35 years to 200 years.

The performance measure used in cross-asset tradeoff analysis, BCR_{ya}, uses only the long-term programmed cost for the alternative selected for each program year in the scoping decision stage. It does not need results for alternatives that were considered but not selected, and it does not use any information about the work selected for the forecast years z. As shown in equation 15, the agency benefit of an investment candidate is computed by subtracting this year's long-term programmed cost from next year's. Thus, the agency benefit is the amount of money saved by acting this year rather than next year. Next year's long-term programmed cost is not further discounted because the entire decision of whether to act is postponed. The tradeoff analysis algorithm assumes that the agency will revisit the decision next year and might decide to delay the work again or might change the selection of treatment category based on the unknown changes in condition that may occur between this year and next.

From year to year, long-term programmed cost usually increases because of continuing deterioration. Long-term agency benefit may be interpreted as the annual rate of change. If this rate is positive, indicating increasing costs, then intervening as soon as funding is available is attractive; if negative, postponing work is attractive, regardless of funding. The model assumes all assets will eventually receive sufficient work to remain open with acceptable LOS, but assets having a higher rate of change in costs will be addressed more quickly to minimize total network costs. Long-term agency benefit is typically a much smaller number than long-term programmed cost, because it is the change in costs caused by only 1 year of delay. This benefit is also typically much smaller than the initial cost of the investment candidate being considered. BCRs are usually less than 1.0 for this reason.

In some cases, a delay of 1 year has no effect at all on long-term programmed costs. This lack of effect is especially the case for asset replacement, whose cost is often insensitive to condition.

Even in this case, however, replacing the asset might reduce near-term maintenance costs and/or user costs, so a positive benefit may still be identified for the investment candidate.

Each program year is evaluated separately, as if no work were done in preceding years. Some management systems automatically generate and store all such investment candidates to support a capability to rapidly generate a range of fiscal scenarios. Systems lacking this capability may need to be modified to generate and export the fiscal scenarios, even if the scenarios are not needed internally, perhaps as a user-selectable option.

Some management systems calculate an amortized version of capital costs, often called the EUAC. Depending on the method used for this calculation, developers may find it easier to compute the benefit estimates directly rather than first computing NPV. Some management systems include routine maintenance costs within their long-term cost analysis, and therefore do not need a separate term for MC_{ya} in equation 15.

To keep the analysis practical and easily implementable, the approach utilized only evaluates a limited subset of all feasible alternatives—comparing the impact of doing the recommended work versus a do-nothing alternative. In theory, the same analysis approach can also be extrapolated to other use cases, such as comparing the impact of doing the recommended work (to achieve the lowest lifecycle cost) to performing a suboptimal treatment (due to financial constraints). This approach would be along the lines of the RSI analysis approach detailed in chapter 2.

Long-Term Agency Benefit Model for Pavements

The long-term benefits achieved from a pavement strategy within the TA-MAPO tool are represented by the long-term cost savings associated with the strategy. A fiscally unconstrained budget scenario was used to generate all the feasible pavement treatment strategies over the chosen analysis period for each pavement segment in the network. Since the TA-MAPO tool compares strategies where a treatment selection is successively delayed over a 10-year period, the savings achieved from a strategy are considered as the increase in the LCC obtained if a treatment is performed in the next year rather than this year. In this study, the strategy that resulted in the lowest LCC of performing a treatment in a given year was selected as the input to the TA-MAPO tool. Once all the feasible strategies were identified, the increase in LCC due to delaying treatments by 1 year at a time was calculated as the potential savings of not delaying treatments over the 10-year timeframe considered in the TA-MAPO tool (FHWA 2024b).

This approach of selecting the pavement investment candidates only considers the lowest LCC scenario based on delaying the recommended treatment by 1 year at a time over the first 10 years. Other suboptimal strategies that may have a lower cost in the first 10 years but a higher LCC were not considered. Pavement investment candidates that are based on fiscally constrained scenarios to serve as inputs to the TA-MAPO tool can also be developed. In an ideal situation, the inputs to the TA-MAPO tool would be exactly the same as the outputs of an RSI analysis. This correspondence would account for all feasible investment candidate options. However, due to the limitations of the current PMS configurations of used by the agencies participating in the validation efforts, the pavement data for the tradeoff analysis only focused on including the best possible investment candidates from a long-term perspective.

Long-Term Agency Benefit Model for Bridges

A distinctive aspect of bridge management is that condition inspections divide each asset into elements, whose conditions are assessed separately by visual inspection. Examples of elements are deck slabs, wearing surfaces, railings, expansion joints, girders, columns, and abutments. The inspector records the quantity of each element found in each of four precisely defined condition states. The definitions of condition states may vary by material; for example, concrete girders may be distinguished from steel girders. Each element has its own deterioration rates and cost structure, determined by analysis of past inspection data. Some agencies use the same type of inspection process for other classes of assets, including sign supports, high-mast light poles, retaining walls, and even unstable slopes.

The planning process in the present study for pilot testing of the proposed methodology found that State DOTs are typically using BMSs capable of producing estimates of long-term agency cost, including routine maintenance cost, calculated in a manner similar to equation 16. However, not all agencies have calibrated their systems to use deterioration rates and costs that are realistic for their inventories. Also, the BMSs appear to lack the ability to export the results of the long-term agency cost calculations for all investment candidates for each program year in the form needed for an external tradeoff analysis. Fortunately, the most commonly used BMSs in North America can be enhanced to provide an export function for an investment candidate file, as described in chapter 4—although not within the timeframe of the present study.

To enable pilot testing of the proposed TAMM, the research team used StruPlan, an open-source spreadsheet for long-range renewal planning for transportation structures (Thompson 2021). StruPlan uses the same inventory and inspection data found in commonly used BMSs in the United States and many of the same predictive models, such as deterioration transition times and unit costs. Because it is focused on network-level use cases, StruPlan is organized in a way that is better-suited to long-range planning applications and able to rapidly generate alternative fiscal and policy scenarios. Most importantly, it produces a worksheet similar in content to the investment candidate file described in chapter 4.

StruPlan divides the task of calculating long-term agency benefits into two parts, as follows:

- A long-term model that estimates agency benefit at the network level as a fraction of replacement value for each type of element and condition state.
- A medium-term model that generates 10 years of investment candidates and estimates benefits for each bridge by applying the long-term unit benefits to the conditions that are forecast on each element of each bridge.

The long-term model is similar in form to equation 16, except that it generates a unit benefit that is applicable to all bridges having a given element in a given condition state. It generates an ergodic Markov chain, a model that converges on a steady long-range annual cost stream after a sufficient number of years, which in practice is always less than 75. It then uses a less-detailed perpetuity model to estimate subsequent long-range costs and give a complete estimate of long-term agency benefits. Routine maintenance costs are included in the cost stream.

In a process that is especially relevant to planning preservation work, StruPlan's long-term model has scenarios for the condition of protective elements, including wearing surfaces, coatings, and sealed expansion joints, so that the deteriorated conditions of these elements produce faster deterioration of substrate elements and therefore higher long-term agency costs.

StruPlan distinguishes the same four treatment categories as the TA-MAPO tool: do nothing (routine maintenance only), preservation, rehabilitation, and reconstruction (Thompson 2021). These categories differ in the way they model indirect costs, such as work zone traffic control and mobilization. Preservation cost modeling is largely proportional to deteriorated quantities, rehabilitation modeling is in between and partially sensitive to condition, and reconstruction cost modeling is insensitive to condition.

In its medium-term model, StruPlan forecasts annual deterioration of each element on each bridge using a hybrid Markov/Weibull model, a form that is receiving increased usage and research in bridge management (Thompson 2021). The long-term unit costs are multiplied by element replacement value and forecast condition to estimate long-term agency costs. The treatment category yielding the lowest total long-term cost is selected, and this same category is used to calculate long-term agency benefit for the investment candidate file.

A typical BMS performs a more detailed long-term cost analysis than StruPlan, considering a more fine-grained menu of possible treatments and analyzing the long-term activity profile separately for each bridge. These calculations require more computational resources but produce a more precise result. The output remains compatible with the proposed methodology, as long as it can be summarized in the form of an investment candidate file, as described in chapter 4.

ESTIMATING USER BENEFITS

A variety of asset characteristics can affect the ability of network links to carry all traffic desiring to use it and the risk that hazards or unexpected events might disrupt the flow of traffic. Both pavements and (more commonly) bridges can have limitations on clearances and load-carrying capacity, which might make it necessary for certain vehicles to detour to an alternate route. Narrow roadways, poor alignment, slippery surfaces, deteriorated surface conditions, and substandard guardrails can all contribute to a higher risk of crashes. External hazards can cause disruptions in transportation service. These hazards include earthquakes, landslides, storm surge, high winds, floods, scour, wildfire, temperature extremes, permafrost instability, overloads, over-height collisions, flammable or hazardous freight collisions, vessel collisions, sabotage, advanced deterioration, and metal fatigue.

A common framework to impose structure and commonality on this diverse set of concerns involves defining a set of hazard scenarios and modeling quantified estimates of the likelihood and consequences of the scenario taking place. Likelihood is typically expressed as a probability, but it may also include the fraction of the traffic stream affected by a functional deficiency. Consequences are usually expressed in dollars and include the value of travel time, vehicle operating costs, costs associated with traffic accidents, and costs of recovering from hazardous events to restore normal traffic flow.

Typically, the likelihood of adverse events is quantified with research into historical events to determine their frequency and their statistical relationship to asset characteristics. The user benefit models commonly used in management systems rely on published research of this type. Consequence models of service disruption also commonly rely on published research, especially the AASHTO Red Book (AASHTO 2010). Standardization is key for this type of analysis. Even if certain factors, such as the economic value of a crash injury, are unknowable, the existence of a published set of metrics used in a wide variety of applications helps ensure that decisions are made in a uniform way, and risks are spread uniformly over the whole network.

The proposed methodology considers user effects of investment candidates in two parts: First, LOS standards compare asset characteristics against a set of standards or thresholds and classify the asset as *Sufficient* if it meets all the standards or *Deficient* if not. Second, for deficient assets appropriate functional improvements are included in the generated investment candidate to cause the asset to satisfy the LOS standards (and often, a higher design standard). User benefit is estimated as the savings in user costs caused by the improvement in asset characteristics.

If a management system uses the pattern represented by equation 14, user costs are computed as a stream of annual cash flows over the entire long-term analysis period, considering traffic growth and sometimes a limitation on growth caused by lane capacity. In the simpler pattern represented by equation 15, only user benefits in the first year are considered. Modeling of traffic growth for equation 14 can be complicated by the fact that, if the traffic growth rate is greater than the discount rate, the total long-term user cost might become infinite. A capacity constraint is one way of avoiding this problem.

LOS standards and the *Sufficient*/*Deficient* classification are also used in computing outcome measures for safety and mobility, as described later in this appendix.

The TA-MAPO tool contains just one worksheet column for each program year to report total user benefits of each investment candidate. The worksheet can be modified if desired to report different types of benefits separately; for example, it can be modified to separate safety, mobility, and sustainability. The TA-MAPO tool does not require user benefits to be reported, and many management systems fail to provide user benefit models. However, certain types of work, especially reconstruction, might not receive sufficient priority in the tradeoff analysis if user benefits are omitted (FHWA 2024b).

User Benefits for Pavements

In typical pavement management applications, the benefit of a treatment is represented by the additional performance provided by the treatment. The benefit is calculated as the area under the performance curve for the treatment being considered, so a treatment with greater impact on performance has greater benefit than a treatment with less impact on performance. User cost savings (i.e., user benefits) in this scenario are typically evaluated in terms of the volume of traffic using a road. By applying an agency-defined traffic factor to the area under the performance curve, a project with higher traffic volume yields greater user benefit than a project with lower traffic volume, corresponding to the same treatment applied to a pavement in a similar condition.

HERS includes a “Highway Investment Analysis Methodology” that, unlike conventional PMSs, analyzes individual highway sections independently rather than as a collective network (FHWA 2005). It uses incremental BCA to compare the benefits and costs of alternative treatment strategies, with benefits defined as reductions in direct highway user costs, agency costs, and societal costs. The user benefits include reductions in travel time costs, crash costs, and vehicle operating costs (e.g., fuel, oil, and maintenance costs) (FHWA 2015).

The Highway Development and Management Model (HDM-4) is a comprehensive software package (and accompanying documentation) consisting of tools for the analysis, planning, management, and appraisal of road maintenance, improvements, and investment decisions. The HDM-4 Road User Costs Model (HDM-4 RUC) (current version 5.0) is a spreadsheet-based model designed to compute, for different vehicle types and road conditions, vehicle speeds, fuel consumption, vehicle operating costs, passenger time costs, emission and accident costs based on HDM-4 relationships (World Bank 2022). The model computes unit road user costs, performs sensitivity analysis, computes network road user costs, and performs a simplified economic evaluation of a road project.

User Benefits for Bridges

All three pilot studies used a set of user cost models provided by StruPlan, all adapted from published sources. These models are summarized in the following sections. More detail can be found in the StruPlan user manual (Thompson 2021). All user benefits are proportional to traffic volume.

Level of Service Standards

StruPlan recognizes user benefits for any bridge that fails to satisfy LOS standards. The following standards are evaluated (Thompson 2021):

- Roadway width, which is compared to a standard calculated using functional class and number of lanes. Each functional class has a standard for lane width and shoulder width. Certain structure design types cannot be widened; in this case, only replacement can relieve the deficiency.

- Vertical clearance, which has a standard that varies by functional class.

- Operating rating, which has a standard that varies by functional class. Depending on the structure design load, strengthening might not be feasible.

Any or all these standards can be deficient on a given bridge, and each type of deficiency has a separate user cost calculation associated with it. Agencies can set the numerical standards—or, if desired, modify the deficiency formulas in the spreadsheet to establish other types of standards.

Safety Benefits for Bridges

StruPlan contains an accident risk model developed in the late 1990s for Florida DOT. This model estimates an average number of crashes per year, which is sensitive to functional class, approach alignment, deck condition, number of lanes, roadway width, bridge length, and traffic volume. The formula is used for both the existing structure and a hypothetical new or widened structure defined using a set of design standards (Thompson 2021). The difference in forecast accident rates is multiplied by a standardized cost per accident, as published in the AASHTO Red Book (AASHTO 2010).

The Florida accident risk model is the only published source of the safety estimates needed for this type of benefit model. Since it is more than 20 years old, it would be a good candidate for new research to update it to fit modern vehicle and roadway characteristics.

Mobility Benefits for Bridges

StruPlan implements truck height and weight histograms developed in research for the Florida DOT in the early 2000s. The models were developed from on-site measurements using laser equipment for height and weigh-in-motion equipment (Thompson 2021). Other agencies may have performed similar research that is useful for planning freight policy and freight networks. Histograms are applied to vertical clearance and operating rating to estimate the fraction of trucks detoured, which is then multiplied by average daily truck volume and detour length. The AASHTO Red Book provides standardized unit costs for travel time and vehicle operating costs, which then provide an estimate of the user cost of truck detours (AASHTO 2010).

StruPlan also implements a scour risk model developed for the Georgia DOT. This model provides a probabilistic estimate of annual scour-related traffic detours and multiplies the estimate by the same unit costs that are in the truck height and weight models (Thompson 2021). Estimating the risk in this way is coarse, but the model does provide a consistent and reasonable way to prioritize scour-related improvements to bridges based on NBI data items (FHWA 2023). NCHRP's *Assessing Risk for Bridge Management: Final Report* provides a framework and examples that can be used for other types of risk models (Thompson et al. 2016).

Environmental Benefits for Bridges

StruPlan contains a model of the public health costs of vehicular emissions, developed in the early 2000s in research for California. The environmental cost is expressed as a cost per vehicle mile, which is added to the vehicle operating cost per mile caused by scour and truck detours to augment the benefit of reducing such detours. The model does not consider carbon dioxide emissions or the effects of climate change (Thompson 2021).

ESTIMATING OUTCOME MEASURES

Pavement Outcome Measures

The TA-MAPO tool documents pavement and bridge conditions in a generic, less-detailed format than FHWA's percent Good and percent Poor measures, as defined in Federal rules (Office of the Federal Register 2017). For each of the pilot States, the project team identified the approach used by the agency to convert their pavement performance indicators to Good/Fair/Poor pavement condition ratings from their corresponding TAMP documents. The following assumptions were used to convert the Good/Fair/Poor pavement condition ratings to *%Good* and *%Poor* as required within the TA-MAPO tool (FHWA 2024b):

- If a pavement segment is rated Good: 100 percent of the pavement segment limits are assumed to be in Good condition.
- If a pavement segment is rated Poor: 100 percent of the pavement segment limits are assumed to be in Poor condition.
- If a pavement segment is rated Fair: 100 percent of the pavement segment limits are assumed to be in Fair condition. Therefore, 0 percent of the pavement segment limits are assumed to be in Good and Poor condition.

Bridge Outcome Measures

StruPlan deterioration models are forecast at the element level using a hybrid Markov/Weibull model (Thompson 2021). However, the TA-MAPO tool needs a more generic, less-detailed format, which is FHWA's percent Good and percent Poor measures, as defined in Federal rules (Office of the Federal Register 2017). StruPlan contains a Weibull model to estimate the probabilities of Good and Poor from element-level condition forecasts. Included in StruPlan is a procedure to estimate the parameters of this Weibull model from inspection data. As a part of the evaluation of a long-term activity profile, StruPlan forecasts element condition at the end of 10 years, then converts this condition to the Good and Poor probabilities. This conversion is then weighted by deck area and summed over all bridges to estimate the network *%Good* and *%Poor* (Thompson 2021).

Because of the need for percent-Good and percent-Poor forecasts for TAMPs and other purposes, BMSs are increasingly providing ways to develop these estimates (Office of the Federal Register 2017).

For safety and mobility, StruPlan adopts a simple approach based on LOS standards. Each bridge is evaluated as Sufficient or Deficient, as described above. The performance measure is the percentage of the inventory (by count) that is classified Sufficient. Bridges that receive a suitable rehabilitation or reconstruction treatment during the program horizon are assumed to be restored to Sufficient performance. Bridges that do not receive rehabilitation or reconstruction remain in the same performance category where they started (Thompson 2021).

APPENDIX F. IDAHO VALIDATION TECHNICAL MEMO

This technical memo summarizes the work activities and results of the Idaho NGPPM and proposed TAMM validation effort. It describes the challenges faced by the project team in conducting the validation and discusses the usefulness of the measures in ITD's pavement management decisionmaking process. Detailed information regarding the validation effort is available in chapter 5 of this report.

NEXT-GENERATION PAVEMENT PERFORMANCE MEASURES VALIDATION PROCESS

The objective of the performance measure validation process was to identify how the measures could help ITD make better pavement management decisions. ITD was interested in finding out whether the performance measures could help narrate an account of its pavement management process that was not currently being told through the use of existing pavement condition-based performance measures (e.g., cracking, rutting, roughness, OCI). To accomplish this objective, the research team gathered and analyzed ITD's pavement management data and computed four financial NGPPMs (ASI, ASR, ACR, and SLR) (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). The research team then presented suggestions to ITD on how the measures could potentially be used to support the existing business processes.

PROPOSED TRANSPORTATION ASSET MANAGEMENT METHODOLOGY VALIDATION PROCESS

In a series of workshops conducted in late 2019, ITD officials were introduced to the proposed tradeoff analysis methodology, as discussed in chapter 3 of this report. The agency was asked to provide, with consultant assistance, spreadsheet files containing pavement segments and bridges, with identification data and 10 years of work candidates, similar to the spreadsheet files used for calculating the NGPPMs. The pavement and bridge data were input to the TA-MAPO tool to enable a demonstration of the use of a benefit-cost prioritization criterion to analyze tradeoffs among costs and conditions across asset classes and subnetworks. The computations within the TA-MAPO tool were then used to produce sample reports addressing performance target feasibility, funding allocation, and funding alternatives, which are all common examples of cross-asset tradeoff analysis.

DATA REQUIREMENTS FOR THE VALIDATION EFFORT

This section presents details on the data and information needs for the NGPPM and proposed TAMM validation process.

Data for Next Generation Pavement Performance Measure Validation

Through several web meetings with FHWA and ITD staff, the project team gathered and finalized parameters and budget levels to be used in the validation effort, summarized as follows:

- Analysis period: 40 years.
- Real discount rate: 2 percent.

- Budget levels: In the range of $70 million to $270 million. ITD ran the analyses using the current strategy followed by the PMS at seven different annual budget levels. However, based on ITD's preferences, only two of the seven budget levels were investigated further as part of the analysis—$85 million and $130 million.

ITD provided a PMS output file covering a 40-year analysis period for each PMS run requested. The following is a summary of the key data fields that ITD provided in their PMS output files:

- Pavement segment description, including the PMS section identifier, pavement type, direction, location, functional class, and the number of lane-miles.
- Pavement treatment recommendations over a 40-year analysis period (treatment type and cost of recommended treatment and backlog of unfunded treatment needs).
- Pavement condition, in terms of ITD's performance indicators. The OCI is a composite index used to represent the overall health of flexible and rigid pavements, as follows:
    - For flexible pavements, the OCI is a function of the SDI and the NDI.
    - For rigid pavements, the OCI is a function of the slab index and the joint index.

Data for Proposed Transportation Asset Management Methodology Validation

Pavement Data

The PMS data output from the multistrategy analysis run by the advanced analysis module is used to generate pavement input to the TA-MAPO tool. ITD provided PMS output files covering a 40-year analysis period with multiple strategies, where the recommended treatments are delayed 1 year at a time over the chosen analysis period for a given segment. The output file also included do-nothing strategy results, which were also used as inputs to the TA-MAPO tool.

Bridge Data

ITD provided bridge and element data (with corresponding metadata) in April of 2020. The dataset included all NHS bridges and all State-owned bridges (1,903 structures in total), including some that did not qualify for the NBI (FHWA 2023). The data used within StruPlan included: bridge data (identifier, district, facility carried, owner, year built and reconstructed, design load, design type and material, length, width, deck area, etc.), data about the roadway carried by the bridge (bypass length, traffic and truck volume, functional class, number of lanes, and roadway width), and inspection data (inspection date, component condition ratings, and element condition records) (Thompson 2021).

These data were provided in text files exported from ITD's BMS. A detailed description of the input data and options available can be found in the StruPlan user manual (Thompson 2021). In general, all the data items provided could also be found in annual submittals to the NBI and complied with FHWA's Coding Guide (FHWA 2023, 1995).

VALIDATION ANALYSES AND RESULTS

This section presents results of the Idaho NGPPM and proposed TAMM validation efforts. Validations of the three lifecycle performance measures—RSI, EUAC, and AUCR—were initially planned, but they could not be performed due to analysis challenges.

Financial Performance Measures

The NGPPM validation efforts focused on the four financial measures summarized in table 2. The validation efforts began with ITD providing the data output files from the requested PMS analysis runs. Once the project team received the data, they analyzed the temporal pavement condition trends by plotting the annual network-level weighted average conditions over the 40-year analysis period.

Figure 10 presents the pavement condition trends (OCI and SDI) for annual budget levels of $85 million, $130 million, and $200 million. The $85 million and $130 million budget levels clearly result in constantly declining conditions over the analysis period. For the $200 million budget level, the OCI appears to plateau through the remainder of the analysis period after the initial decline over the first 7 years. The SDI trends show an appreciable improvement (approximately 15 percent) over the last 15 years of the analysis period.

Pavement need and asset value depreciation calculation were two crucial components in calculating the financial performance measures. The pavement need is the annual funding level required to meet the desired SOGR. The desired SOGR was established using the SDI and OCI based on input from ITD, where a functional desired SOGR keeps the overall pavement network at an upper Fair OCI condition (i.e., OCI ≥ 73) and a structural desired SOGR reduces the need for major treatments (SDI ≥ 75).

Since an annual budget of $200 million meets the desired SOGR, this value was used to establish the pavement need. The asset value depreciation was calculated using a simple piecewise linear depreciation approach, as the ITD PMS did not inherently calculate it. Table 67 and table 68 summarize the assumptions the project team used to calculate the asset value depreciation for flexible and rigid pavements, respectively.

Table 67. Flexible pavement treatment recommendations based on SDI targets.

Treatment Type	Treatment Unit Cost (dollars)	SDI Targets			
		Statewide Segments	Interstate Segments	Regional Segments	District Segments
Preservation—Flexible	29,442	100−75	100−80	100−70	100−65
Resurfacing—Flexible	68,358	75−60	80−65	70−55	65−50
Restoration—Flexible	304,980	60−40	65−45	55−35	50−30
Rehabilitation—Flexible	437,333	40−25	45−30	35−20	30−15
Reconstruction—Flexible	1,498,862	25−0	30−0	20−0	15−0

Table 68. Rigid pavement treatment recommendations based on OCI targets.

Treatment Type	Treatment Unit Cost (dollars)	OCI Targets
Preservation—Rigid	188,877.00	100−80
Restoration—Rigid	377,753.60	80−60
Rehabilitation—Rigid	1,087,916.48	60−30
Reconstruction—Rigid	1,438,796.80	30−0

After the research team identified and calculated all the essential elements, they calculated the four financial measures summarized in table 2 using the pavement data from the PMS runs that corresponded to the current strategy at the annual budget levels of $85 million and $130 million. The analysis results and inferences from the calculations are summarized in chapter 5.

Proposed Transportation Asset Management Methodology Validation

A detailed discussion of this topic appears in the Cross-Asset Trade-off Analysis and Results section in chapter 5. Figure 18 in chapter 5 shows an example of how the TA-MAPO tool provides a graphical representation comparing the 10-year forecast performance against specified targets for any defined subsets of the network from the ITD pilot study.

The research team observed that Idaho's pavements appeared to be in considerably better condition than its bridges, although both assets compare favorably with national standards. This comparison was borne out in the funding allocation analysis illustrated in figure 19, which shows that, when the same benefit-cost prioritization measure is used for both pavements and bridges, their conditions tend to move closer together. Thus, bridge conditions tend to improve at the expense of pavement conditions (FHWA 2024b).

Decisionmakers often find it intuitive that an increase in funding for infrastructure renewal should result in better conditions. The TA-MAPO tool has a worksheet geared toward evaluating this tradeoff quantitatively. Figure 20 shows an example of the improvement in NHS condition that may result from an increase in funding for pavements and bridges. When interpreting this graph, pavement and bridge measures are combined in a weighted average by replacement value. This weighting is different from the Federal performance measures, which weight pavements by lane-miles and bridges by deck area. Also, note that the standards used in defining Good and Poor are fundamentally different for pavements and bridges. Therefore, the graph gives a general impression of the relative effect on performance but does not directly forecast a Federal measure.

APPENDIX G. SOUTH DAKOTA VALIDATION TECHNICAL MEMO

This technical memo summarizes the work activities and results of the South Dakota NGPPM and proposed TAMM validation effort. It describes the challenges the project team faced in conducting the validation and discusses the usefulness of the measures in SDDOT's pavement management decisionmaking process. Detailed information regarding the validation efforts is available in chapter 6 of this report.

NEXT-GENERATION PAVEMENT PERFORMANCE MEASURES VALIDATION PROCESS

The objective of the performance measure validation process was to identify how the measures could help SDDOT make better pavement management decisions. Initially, the SDDOT team was interested in investigating the advantages and disadvantages of using the NGPPMs and comparing the results of the lifecycle strategy generated through the RSI analysis to the lifecycle strategy selected by the PMS. To accomplish this objective, the research team gathered and analyzed SDDOT's pavement management data, conducted the RSI analysis, and computed four financial NGPPMs (ASI, ASR, ACR, and SLR) (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). The research team then presented suggestions to SDDOT on how the measures could potentially be used to support the existing business processes.

PROPOSED TRANSPORTATION ASSET MANAGEMENT METHODOLOGY VALIDATION PROCESS

In a series of workshops conducted in the summer of 2020, the research team introduced SDDOT officials to the proposed tradeoff analysis methodology. The research team asked the agency to provide, with consultant assistance, spreadsheet files containing pavement segments and bridges, including identification data and 10 years of work candidates. Since the SDDOT PMS did not have the capability to output the needed spreadsheet directly, the research team needed to develop a separate spreadsheet model to accumulate PMS data and calculate the performance measures from multiple PMS analytical runs. Similarly, SDDOT's BrM was not capable of outputting a full set of work candidates in the needed format, so an open-source spreadsheet program (StruPlan) was used to develop the appropriate work candidates (AASHTO 2023; Thompson 2021). Therefore, the research team asked SDDOT to provide a dataset compatible with StruPlan (Thompson 2021).

The research team combined work candidates generated in this way from pavement and bridge data into the TA-MAPO tool's assets worksheet (chapter 4), forming an investment candidate file with the necessary prioritization measures and performance outcomes. The computations within the TA-MAPO tool were then used to produce sample reports addressing performance target feasibility, funding allocation, and funding alternatives, which are all common examples of cross-asset tradeoff analysis.

DATA REQUIREMENTS FOR THE VALIDATION EFFORT

This section presents details on the data and information needs for the NGPPM and proposed TAMM validation process.

Data for Next Generation Pavement Performance Measure Validation

The research team worked closely with SDDOT pavement management staff to gather all the necessary parameters and budget levels needed for the validation study. The parameters and strategies finalized for the study are summarized as follows:

- Analysis period: 30 years.
- Real discount rate: 3.32 percent.
- Annual budget level: $16.7 million.
- Performance target: 3.7 weighted average SCI.
- Analysis corridor: US-14 (rural minor arterial road with 118 segments and 579 lane-miles).

For the NGPPM validation, SDDOT ran the following scenarios:

- Current budget level.
- Current budget plus 20 percent.
- Current budget minus 20 percent.
- Unlimited budget (no budget constraint).

To conduct an RSI analysis, the research team also requested SDDOT provide the outputs from the multistrategy analysis, which contained all the lifecycle strategies evaluated by the PMS for the US-14 corridor.

Finally, SDDOT provided a PMS output file covering a 30-year analysis period for each PMS run requested. The key data fields that SDDOT provided in their PMS output files are summarized as follows:

- Pavement segment description, including the pavement segment name, road name, pavement type, size (centerline miles), location, functional class, and the number of lane-miles.

- The 30-year treatment suggestions (treatment type and cost).

- Pavement condition in terms of SCI.

Although the PMS runs were conducted using a 30-year analysis period, the performance measure validation efforts only considered the results from 25 years.

Data for Proposed Transportation Asset Management Methodology Validation

Pavement Data

The SDDOT PMS's ability to conduct a multistrategy analysis is conducive to generating inputs for the TA-MAPO tool. SDDOT provided output files from a multistrategy analysis run covering a 30-year analysis period. However, the generated strategies are not based on delaying treatments by 1 year at a time. The TA-MAPO tool requires data from strategies where the suggested treatments are delayed 1 year at a time over the chosen analysis period. Thus, the project team had to manually adjust the strategies generated by the PMS to generate the inputs in a format that was compatible with the TA-MAPO tool. The PMS analysis also included the results of a do-nothing strategy and a maintenance-only strategy, and these results were also used as inputs to the TA-MAPO tool (FHWA 2024b).

Bridge Data

Since ITD's BMS was incapable of generating the bridge work candidates necessary for the TA-MAPO tool, StruPlan's data outputs were used. SDDOT provided a copy of appropriate tables from its BMS database in July 2020. The dataset included all NHS bridges and all State-owned bridges (1,803 structures in total). The data used in the StruPlan included the following data from SDDOT outputs (Thompson 2021):

- Bridge (identifier, district, facility carried, owner, year built and reconstructed, design load, design type, and material, length, width, deck area, etc.).
- Roadway carried by bridge (bypass length, traffic and truck volume, functional class, number of lanes, and roadway width).
- Inspection (inspection date, component condition ratings, and element condition records).

These data were provided in text files exported from ITD's BMS. A detailed description of the input data and options available can be found in the StruPlan user manual (Thompson 2021). In general, all the data items provided can also be found in annual submittals to the NBI and complied with FHWA's Coding Guide (FHWA 2023, 1995).

VALIDATION ANALYSES AND RESULTS

This section presents results of the South Dakota NGPPM and proposed TAMM validation efforts.

Lifecycle Performance Measures

The NGPPM validation efforts focused on the three lifecycle measures summarized in table 1. The validation efforts began with SDDOT providing the data output files from a multistrategy analysis run, and the requested PMS analysis runs. Once the data were received, the project team used the outputs from the multistrategy analysis to generate several alternative lifecycle strategies using the RSI approach that met the established performance requirement (SCI ≥ 3.7) and LOS threshold (IRI ≤ 130 inches per mi). Two alternative strategies from the RSI analysis are presented in the analysis results:

- RSI-U: Lowest LCC strategy in the absence of any budget constraints.
- RSI-C: Lowest LCC strategy based on the current budget level established for the US-14 analysis corridor.

The project team compared the RSI-U and RSI-C strategies with the following analysis runs in SDDOT's PMS:

- MBCB: Analysis run at the current budget level.
- MBCB+20: Analysis run at a 20-percent higher budget level.
- MBCB−20: Analysis run at a 20-percent lower budget level.
- MBU: Analysis run with no budget constraints.

The project team then analyzed the pavement condition trends by plotting the annual network-level weighted average conditions over the 25-year analysis period. Figure 21 presents the SCI trends for the following strategies evaluated: MBCB, MBCB+20, MBCB−20, MBU, RSI-U, and RSI-C. As can be seen, the condition trends can be divided into two distinct zones. Zone 1 extends from year 0 through year 7, where the pavement condition constantly declines from a starting SCI value of approximately 4.2 (even for the unlimited budget strategy). The declining conditions observed in zone 1 are due to lower investment levels since the pavements are generally above the established SCI target. In zone 2, which extends from year 8 through year 25, the conditions gradually start to improve. As expected, better pavement conditions are achieved with an increased budget, with the MBU strategy (unlimited budget strategy) resulting in significant condition improvements from year 8. The pavement conditions for all the other strategies fall below the established condition target between year 7 and year 11, after which they start to improve. At the end of year 25, the MBCB−20 strategy (20-percent budget reduction) is the only strategy that results in a network-level SCI significantly lower than the established performance target.

Figure 22 shows the IRI trends for each strategy evaluated. As can be seen, all the strategies successfully maintained IRI values below 130 inches per mi over the 25-year analysis period. Based on the performance thresholds established under FHWA's National Highway Performance Program, these levels of roughness correspond to Good (IRI < 95 inches per mi) or Fair (IRI 95–170 inches per mi) conditions, as per 23 CFR 490 (CFR 2016a).

The asset value depreciation and LCC calculation were the two crucial components in validating the lifecycle measures. The asset value depreciation was calculated using a simple piecewise linear depreciation approach since the SDDOT PMS does not inherently calculate it. Table 69 and table 70 summarize the assumptions used in calculating the asset value depreciation for flexible and rigid pavements, respectively.

Table 69. Flexible pavement treatment recommendations based on SCI targets.

Treatment Type	Treatment Unit Cost (dollars)	SCI Upper Bound
Highway Preservation	147,733	3.7
Highway Rehabilitation	469,767	2.5
Highway Reconstruction	1,539,131	1.4

Table 70. Rigid pavement treatment recommendations based on SCI targets.

Treatment Type	Treatment Unit Cost (dollars)	SCI Upper Bound
Highway Preservation	23,462	4.18
Highway Rehabilitation	805,312	2.94
Highway Reconstruction	1,660,944	1.24

The LCC calculation is essential in identifying the optimal lifecycle strategy used to calculate the lifecycle performance measures. The project team used three approaches in calculating the LCC for each strategy evaluated, summarized as follows:

- PV: This approach calculates LCC by aggregating the PVs of treatment costs over the 25-year analysis period.
- PV + RV: This approach includes the PVs of treatment costs and the RVs of the treatments when their service lives extend beyond the end of the analysis period. A simple straight-line model is used to determine the RV. The estimated service life of each treatment category used in the analysis is summarized in table 71.
- PV + cost to restore: This approach adds the cost to restore the condition of the pavement segment close to the as-built condition to the PV of treatment costs over the 25-year analysis period.

Table 71. Assumptions regarding treatment service life.

Treatment	Service Life (years)
Preservation	5
Resurfacing	8
Restoration	10
Reconstruction—Flexible	18
Reconstruction—Rigid	33

Once all the essential elements were identified and calculated, the three lifecycle measures summarized in table 1 were calculated. This section presents analysis results and inferences from the calculation.

Remaining Service I Analysis

The research team compared the results of the PMS analysis run at the four budget levels (MBCB, MBCB+20, MBCB−20, and MBU) to the two strategies (RSI-U and RSI-C) generated using the RSI analysis. Comparisons were also made in terms of future pavement conditions, annual variation in treatment cost, LCC, and the effect of different discount rates.

A comparison of the pavement condition trends for each strategy evaluated was presented in figure 21 and figure 22. The short-term (10-year) and long-term (25-year) Good/Fair/Poor condition outcomes for each strategy are presented in this section. For this analysis, condition was delineated by the following SCI ranges: Good ($3.4 \leq \text{SCI} \leq 5.0$), Fair ($2.1 \leq \text{SCI} < 3.4$), and Poor ($\text{SCI} < 2.1$).

Figure 25 illustrates the conditions at the start of the analysis and the conditions achieved at year 10 and year 25 for each of the six strategies evaluated. As shown, at the start of the analysis, 92 percent of the pavements are in Good condition and the remaining 8 percent are in Fair condition.

At year 10, the strategies with higher budget levels resulted in better conditions, as expected. The MBU strategy resulted in 96 percent of the pavements in Fair or better condition, while the MBCB+20 strategy resulted in 87 percent of the segments in Fair or better condition. The MBCB and MBCB−20 strategies resulted in 83 percent of the pavements in Fair or better condition, while the RSI-C strategy resulted in 79 percent of the network in Fair or better condition. Lastly, the MBCB strategy yielded a slightly better outcome (Fair or better condition) than the constrained RSI analysis.

The condition outcomes at year 25 are significantly different from the 10-year outcomes, further emphasizing the importance of considering a longer analysis period. The condition outcomes from the RSI analysis-based strategies (RSI-U and RSI-C) are comparable to the MBCB strategy's outcomes, with each strategy resulting in 93 percent in Fair or better condition.

Figure 27 shows the LCCs calculated for each evaluated strategy.

The key findings from the LCC comparisons are as follows:

- The RSI-U strategy represents the lowest LCC strategy that meets established performance constraints in a fiscally unconstrained scenario. In contrast, the MBU strategy generated by the SDDOT PMS resulted in the highest LCC.
- The LCC calculated using the PV + RV approach resulted in the lowest value when compared to the other two approaches, due to the inclusion of the remaining value of treatments beyond the analysis period (which is a negative dollar amount). The RV estimates for the strategies generated using SDDOT's PMS were generally higher since the PMS triggered more reconstruction treatments (particularly in the later years) that had longer service lives.
- The constrained RSI strategy (RSI-C) has a slightly lower LCC when compared to the MBCB strategy generated using the PMS. However, the differences are minor. The approach used by SDDOT's PMS seems to result in outcomes that are close to the lowest LCC strategy even though the analysis does not explicitly consider LCC in the optimization routine.
- The LCC of the RSI-C strategy is similar to that of the MBCB−20 strategy. However, the MBCB−20 strategy results in a significant decline in the pavement condition after year 21. At the end of the analysis period, the SCI value drops to 3.38, which is below the established target.

Cost Accrual Ratio

For validation purposes, the research team calculated both short-term and long-term CAR values for each strategy. In addition, the RSI-C strategy was considered the optimized lifecycle strategy, as it represented the lowest LCC strategy that met the established budget and performance constraints.

Figure 29 illustrates the variation in short-term CAR calculated for each strategy. As can be seen, all these strategies except the MBU strategy are fairly consistent with the optimized strategy in terms of the investments made. In addition, while the RSI-U strategy shows significantly higher investments when compared to the RSI-C strategy over the first 3 years, the CAR values drop below a value of 1 from year 5 onward. The RSI-U strategy represents the lowest LCC strategy; however, it does not meet the established annual budget constraints. Thus, it is not a practical strategy to consider from an implementation standpoint. The MBCB−20 strategy exhibits CAR values that are quite similar to the CAR values for the RSI-C strategy; however, the performance levels achieved through the MBCB−20 strategy are noticeably lower.

The long-term CAR trends (figure 30) provide quick feedback on the number of years for each strategy to use 100 percent of the planned investments based on the optimized strategy. As figure 30 shows, the MBU strategy takes only 10 years to spend the total planned investments based on the RSI-C strategy, whereas the MBCB strategy takes approximately 20 years to invest the same amount.

Annualized Unit Cost Ratio

The AUCR was calculated for each strategy using the programmed annualized unit cost and the optimized annualized unit cost. As with the CAR validation, the RSI-C strategy was considered the optimized lifecycle strategy; therefore, its AUCR value was one.

Figure 31 shows the AUCR values calculated for each strategy over the 25-year analysis period. As can be seen, the AUCR for the MBCB strategy was almost 20 percent higher than the AUCR for the RSI-C strategy, and the AUCR for the MBCB+20 strategy was almost 30 percent higher than the AUCR for the RSI-C strategy.

Financial Performance Measure Validation

The NGPPM validation also focused on the four financial measures summarized in table 2. The financial measure validation efforts began with SDDOT providing the data output files from the requested PMS analysis runs. The project team received the data and analyzed the temporal pavement condition trends over the 25-year analysis period, as was illustrated in figure 21.

Two crucial components in validating the financial measures were pavement need and asset value depreciation. The pavement need is the annual funding level required to meet the desired SOGR. The desired SOGR was established using the SCI based on an SDDOT-established performance requirement of SCI ≥ 3.7. SDDOT's current strategy (MBCB) was found to maintain a network-level SCI of 3.7 over the analysis period. Hence, the MBCB strategy was primarily used to establish the pavement need. The asset value depreciation was calculated using the approach described in chapter 6.

Once all the essential elements were identified and calculated, the research team produced three of the four financial measures (ASI, ASR, and ACR) summarized in table 2 (Proctor, Varma, and Varnedoe 2012; Howard, Dixon, and Comrie 2011; Ram et al. 2023). The analysis results and inferences for these measures are presented in this section. Although the research team made various attempts to calculate the SLR financial measure, it could not be validated using the outputs from SDDOT's PMS.

Asset Sustainability Index

Figure 32 shows the ASI trends over the 25-year analysis period. In zone 1, the ASI for all the strategies gradually decline due to lower investment levels in the first 7 years of the analysis. The investments in preservation and major rehabilitation begin to increase at year 8, and the ASI for all the strategies except MBCB−20 show a slight upward trend through year 17, after which they plateau. All the strategies generally indicated that an investment of at least 70 percent of the needs maintains the pavement at the desired SOGR.

At the end of the 25-year analysis period, the MBCB+20 strategy resulted in an ASI of 1, whereas the ASI for the MBCB and RSI-C strategies after this time were approximately 0.9. The MBCB−20 strategy was able to satisfy only 78 percent of the pavement needs and resulted in the pavement condition declining to 3.6. The other strategies resulted in the SCI being maintained at approximately 3.8.

Asset Sustainability Ratio

Figure 33 illustrates the ASR trends over the 25-year analysis period. In zone 1, the planned investments were significantly lower than the needs; thus, they were not adequate to offset the depreciation accumulated in the first 7 years. However, with the significant increases in investments in zone 2, the ASR jumped above the 70 percent mark for all the strategies except the MBCB−20 strategy.

At the end of the 25-year analysis period, the MBCB+20 strategy resulted in the highest ASR (approximately 0.93). The ASR for the MBCB and RSI-C strategies after 25 years were close to 0.8, whereas the value for the MBCB−20 strategy was approximately 0.6. These projections indicate that, with a 20 percent reduction in the budget, SDDOT will only be able to offset 60 percent of the accumulated pavement depreciation.

Asset Consumption Ratio

Figure 34 shows the ACR trends over the 25-year analysis period. These trends are similar to the pavement condition trends illustrated in figure 21. The ACR measure is not as sensitive to depreciation or investments as the other measures discussed, since ACR compares asset value depreciation to the replacement value of the pavement network (which is a significant value). All the strategies investigated were able to maintain an ACR of 70 percent or higher over the 25-year analysis period.

At the end of the analysis period, the MBCB, MBCB+20, and RSI-C strategies resulted in an ACR of approximately 0.84; meanwhile, the MBCB−20 strategy resulted in an ACR of 0.74. These results are consistent with the findings from the lifecycle measure validation, where the MBCB−20 strategy, though similar to the RSI-C strategy in terms of LCC, resulted in a lower percentage of pavements in Fair or better condition.

Proposed Transportation Asset Management Methodology Validation

The TA-MAPO tool provides a graphical representation comparing forecasted 10-year performance against specified targets for any defined subsets of the network (FHWA 2024b). Table 12 and figure 35 show tabular and graphical examples, respectively, of a StruPlan performance forecast, using the SDDOT-specified fiscal scenario with a first-year cost of $68.44

million. SDDOT specified a 4-percent inflation rate for bridge costs, representing an annual decline in buying power and no real growth. The funding was sufficient to increase the percent-Good performance measure to 34.88 percent after 10 years and reduce the percent-Poor measure to 2.72 percent for the combined total of NHS and State-owned bridges (Thompson 2021).

The South Dakota pilot test of a cross-asset tradeoff analysis was not fully successful because of the difficulty in computing a consistent benefit-cost performance measure in the PMS and the inability of the PMS to generate enough cost-effective projects to maintain current conditions and spend the available budget. Most pavement BCRs were outside of the expected range of zero to one; thus, they were either above or below the range of bridge projects. As a result, the TA-MAPO tool was unable to produce meaningful results for resource allocation or sensitivity to funding levels.

Diagnosis of the problems observed in the data led the research team to refine the methodology specification to clarify the LCC requirements and expected range of BCRs. The revised description is reflected in chapter 3, chapter 4, and appendix E.

The research team noticed another set of issues in the data: Classifying pavement resurfacing projects as either preservation or rehabilitation was difficult, and resurfacing made up more than half of the total cost of pavement projects. Resurfacing fits the definition of preservation in that it protects the pavement structure from deterioration and improves the pavement condition. However, resurfacings thicker than 1.5 to 2 inches that impart added structural life to the pavement are generally classified as rehabilitation. In the case of the South Dakota analysis, counting resurfacing projects as preservation resulted in preservation making up 67.58 percent of the pavement investment in the combined program. However, counting resurfacing projects as rehabilitation resulted in preservation making up only 14.88 percent of the pavement investment.

The research team made another important observation in the data, which was the importance of quantifying all the benefits of pavement work. The PMS primarily relies on a decision tree to mandate reconstruction if a pavement deteriorates to sufficiently bad condition. It does not attempt to quantify the benefit to road users of this work. This reliance on a decision tree makes it difficult to implement any type of cross-asset tradeoff analysis, as the decision rules are specific to pavements and not applicable to bridges or any other asset class. However, the bridge analysis employs a user cost model to quantify the benefits of bridge reconstruction. Meanwhile, other available tools for cross-asset analysis, such as FHWA’s HERS, employ user cost models for both pavements and bridges so that cross-asset tradeoffs can be analyzed (FHWA 2005).

APPENDIX H. TEXAS VALIDATION TECHNICAL MEMO

This technical memo summarizes the work activities and results of the Texas NGPPM and proposed TAMM validation effort. It describes the challenges the project team faced in conducting the validation and discusses the usefulness of the measures in TxDOT's pavement management decisionmaking process. Detailed information regarding the validation efforts is available in chapter 7 of this report.

NEXT-GENERATION PAVEMENT PERFORMANCE MEASURES VALIDATION PROCESS

The objective of the performance measure validation process was to determine the usefulness of the measures in the pavement management decisionmaking process for TxDOT. TxDOT was interested in finding out whether the performance measures could help narrate an account of its pavement management process not being communicated by existing pavement condition-based performance measures (e.g., cracking, rutting, roughness, OCI). To accomplish this objective, the research team gathered and analyzed TxDOT's pavement management data and computed four financial NGPPMs (ASI, ASR, ACR, and SLR) (Proctor, Varma, and Varnedoe 2012; Ram et al. 2023). The research team then presented suggestions to TxDOT on how the measures could potentially be used to support the existing business processes.

PROPOSED TRANSPORTATION ASSET MANAGEMENT METHODOLOGY VALIDATION PROCESS

Detailed pavement and bridge data for two districts (Houston and Brownwood) were requested and provided by TxDOT and then entered into the TA-MAPO tool to analyze tradeoffs between costs and conditions across asset classes and subnetworks. A separate spreadsheet model was used to accumulate PMS data and calculate the performance measures from multiple analytical runs. Additionally, the StruPlan spreadsheet program was used to generate bridge work candidates (Thompson 2021). These candidates were then combined with pavement work candidates to form the investment candidate file used in the TA-MAPO tool.

DATA REQUIREMENTS FOR THE VALIDATION EFFORT

This section presents details on the data and information-gathering efforts for the performance measure validation process.

Data for Next Generation Pavement Performance Measure Validation

The research team worked closely with the TxDOT pavement management staff to gather all the necessary parameters and budget levels needed for the validation study. The following is a summary of the parameters and strategies finalized for the study:

- Analysis period: 20 years.
- Discount rate: No discount rate or inflation rate was considered (real discount rate = 0 percent).
- Annual budget level: Current budgets used during the scenario runs were $100 million per year for Houston District and $29 million per year for Brownwood District.

- Additional budget scenario runs for each district:
    - 15-percent reduction in funding level.
    - 30-percent reduction in funding level.
- Analysis network, Houston District:
    - Number of segments: 3,306.
    - Total lane-miles: 11,546.
    - Pavement type distribution: CRC (54 percent), AC (43 percent), JPC (3 percent).
    - Roadway setting classification: Urban.
- Analysis network, Brownwood District:
    - Number of segments: 1,906.
    - Total lane-miles: 5,976.
    - Pavement type distribution: AC (100 percent).
    - Roadway setting classification: Rural.

Data for Proposed Transportation Asset Management Methodology Validation

Pavement Data

Since TxDOT's PMS was not configured to generate strategies based on delaying treatments by 1 year at a time, the project team used the results of the do-nothing scenario run to generate inputs in a format compatible with the TA-MAPO tool. The do-nothing scenario provides details on treatments that will be triggered over the analysis period if funding is available. This information, in conjunction with TxDOT's treatments decision trees, was used to develop a simplified process to generate the inputs required for the TA-MAPO tool. Although the TA-MAPO tool conducts the analysis over a 10-year period, the PMS analysis was conducted for a 20-year analysis period to evaluate the long-term impact (in terms of change in LCC) of delaying treatments.

Bridge Data

At the time of the validation study, TxDOT was in the early stages of implementing the AASHTOWare BrM software (AASHTO 2023). It did not yet have full statewide coverage of element data for non-NHS bridges and had not developed element-level deterioration or cost models suitable for LCCA. The agency provided a complete file containing the statewide NBI data it had submitted to FHWA in 2021 (FHWA 2023). For compatibility with the pavement analysis, these data were pared down to just the Houston and Brownwood districts. The final dataset contained 2,216 bridges, all of which were State-owned bridges on the NHS.

These data were provided in text files exported from ITD's BMS. A detailed description of the input data and options available is in the StruPlan user manual (Thompson 2021). In general, all the data items provided were also found in annual submittals to FHWA's NBI and complied with FHWA's Coding Guide (FHWA 2023, 1995).

StruPlan was employed to generate investment candidates with the necessary performance measures for prioritization and outcome forecasting (Thompson 2021). The deterioration model was derived from the NBIAS for climate zone 6 (damp warm) (Cambridge Systematics 2011).[31] StruPlan's default cost models, which were obtained primarily from Kentucky bid tabulations, were used.

VALIDATION ANALYSES AND RESULTS

This section presents results of the Texas NGPPM and proposed TAMM validation efforts. Although the research team initially planned validations of the three lifecycle performance measures—RSI, AUCR, and CAR—these validations could not be performed due to the limitations of the agency's PMS.

Financial Performance Measures

The NGPPM validation efforts focused on the four financial measures summarized in table 2. The financial measure validation efforts began with TxDOT providing the data output files from the requested PMS analysis runs. Once the data were received, the project team analyzed the pavement condition trends and percent lane-miles of pavement in Good or Better condition (CS ≥ 70) for each district over the 20-year analysis period. The resulting pavement condition trends and percent lane-miles in Good or Better condition for the Houston and Brownwood districts are illustrated in figure 37 and figure 38.

Two crucial components in validating the financial measures are the pavement need and asset value depreciation. The pavement need is the annual funding level required to meet the desired SOGR. TxDOT's desired SOGR was to maintain 90 percent of lane-miles in Good or Better condition. The asset value depreciation is calculated using the approach described in chapter 7. Once all the essential elements were identified and calculated, the four financial measures summarized in table 2 were calculated for each district.

Proposed Transportation Asset Management Methodology

The pavement and bridge data prepared separately in their respective spreadsheet tools were combined into the investment candidate file in the TA-MAPO tool. No problems were encountered in this step. However, the investment candidates did manifest some of the same problems encountered in the other pilot studies; particularly, there were not enough pavement projects with a BCR greater than zero to maintain current conditions or spend the available funding. This limitation was not a problem with the identified projects but was more of an issue for the PMS. The PMS did not rely on LCCs for project justification. In the bridge management analysis, the deterioration and cost models were not Texas-specific, so their accuracy could not be adequately assessed for use in Texas.

In spite of these issues, the TA-MAPO tool did have enough information to demonstrate the desired tradeoff behavior. For example, the weights assigned to condition, safety, and mobility affected forecast outcomes in the expected ways in a sensitivity analysis. Additionally, adding weight to safety caused an increase in the priority of bridge-widening projects. This increase reduced road user costs and improved safety performance. Changes in the total funding provided to the model had the expected effects on performance outcomes—more funding produced better conditions (figure 54) (FHWA 2024b).

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[31] FHWA. 1999–2024. *NBIAS* investment analysis tool (software).

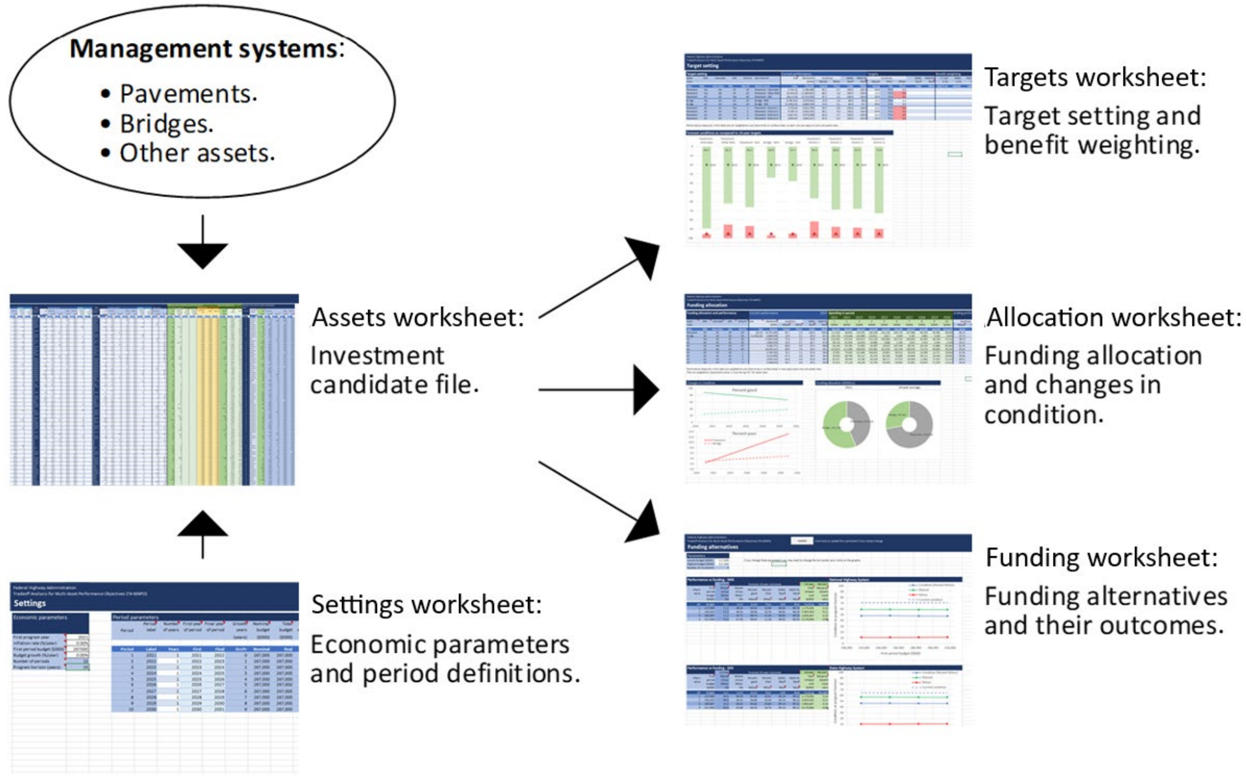
Because of the inability of both the PMS and BMS to perform LCCA, the data available for TA-MAPO testing were less realistic than the other pilots. They provided the desired validation of the TA-MAPO tool, but further implementation of pavement and bridge management within TxDOT will be required to assess the usefulness of a cross-asset methodology for decisionmaking.

APPENDIX I. TRADE-OFF ANALYSIS FOR MULTI-ASSET PERFORMANCE OBJECTIVES TOOL (FHWA 2024B)

OVERVIEW

The TA-MAPO tool consists of five worksheets and a few formulas and macros. The tool is operable under any version of Microsoft® Excel® after 2007 (Microsoft 2024). For correct operation, Excel security settings must be set in the Trust Center to allow macros, with or without notification. The macros serve to automate certain repetitive calculations that reuse parts of the worksheets (e.g., to perform benefit-cost ranking in the same way for each year of the program). Microsoft's technical support provides instructions on how to change macro security settings in Excel to allow macros (Microsoft 2023).

An overview of the tool is provided in figure 56. Agency management systems provide the source data, which may pertain to pavements, bridges, or any other class of assets. Data may be entered on the assets worksheet manually, by copying and pasting, or by using any of the data import or data query features provided by Excel (Microsoft 2024). Work candidate data are typically organized into annual or biennial budget cycles, which can be configured on the settings worksheet.



Source: FHWA.

Figure 56. Illustration. Layout of TA-MAPO spreadsheet tool.

Three prototype worksheets support presentation and manipulation of funding and performance tradeoffs. These worksheets include the following:

- Targets worksheet: Presents a breakdown of performance outcomes by performance concern and subnetwork. Compares forecast performance against targets. Supports the application of weight factors, if desired, to redirect resources and thereby change forecast outcomes.
- Allocation worksheet: Presents an annual spending plan and the relative expenditure on system preservation actions, summarizing the change in performance between current levels and 10-year forecasts.
- Funding: Supports the generation of alternative funding scenarios so that the forecast outcomes can be compared.

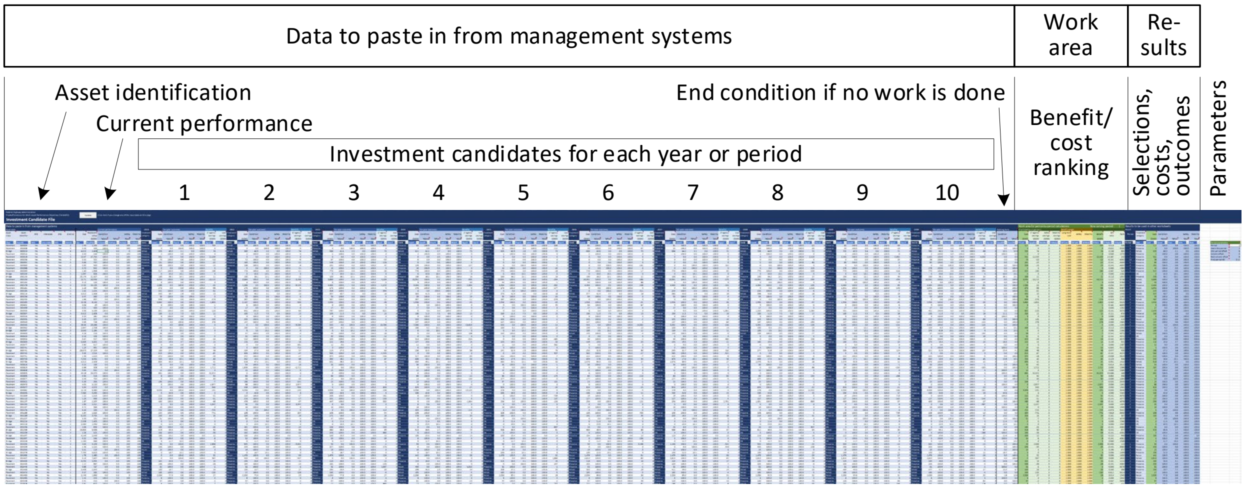
Alternative policy scenarios can be generated and saved in separate spreadsheet files. Portions of the network, such as districts, can be organized into separate spreadsheet files if desired. The selection of reports provided with the spreadsheet is basic, but agencies can add reports that serve their own business needs.

INVESTMENT CANDIDATE FILE AND ASSETS WORKSHEET

The concept of an investment candidate file was first described in the AASHTO *Asset Management Guide* as a basis for a variety of planning activities, especially those that involve multiple classes of assets (AASHTO 2011). An investment candidate file provides a standardized way of reporting work candidates that can be applied to any class of physical assets for which program planning is conducted.

When the research team interviewed State DOTs for potential pilot participation, they realized it would be challenging for the agencies to produce an investment candidate file as envisioned in the AASHTO *Asset Management Guide* (AASHTO 2011). However, many agencies were using management systems with forecasting and planning capabilities. Many agencies had responded to the Federal management system requirements in 23 CFR 515 by engaging in research and development activities to improve their management systems so that the desired information could be produced (CFR 2021b). This study is meant to provide conceptual development for the next generation of TAM decision support, 10 or more years in the future, when the current trends in research and development will most likely have advanced to the common use of performance management tools, such as benefit-cost prioritization and LCCA (FHWA 2024a, 1998). Therefore, the TA-MAPO tool was designed to accept data that future management systems are expected to supply.

Figure 57 is a screenshot of the TA-MAPO tool's assets worksheet, which implements an investment candidate file.



Source: FHWA.

Figure 57. Illustration. Screenshot of the assets worksheet within the TA-MAPO tool.

The rows of the worksheet are individual assets, such as bridges or pavement sections. Alternatively, they may be larger investment units, such as groups of assets, or even groups of similar elements of a large set of assets (for example, all bridge decks of a given type). The columns contain data in the following groups:

- Asset identification: Data that identify the individual rows, relate them to other data stores using a unique identifier, and classify the assets according to subnetwork. Each asset has a size and replacement value, which are used when computing network-level weighted averages of outcome measures.

- Current performance: Outcome measures in the form of *%Good* condition, *%Poor* condition, *%Sufficient* condition for safety, and *%Sufficient* condition for mobility, computed as discussed in chapter 3 from current condition and performance data.

- Investment candidates: Each year in the program horizon (usually 10 years) identifies a selected treatment, its cost, its forecasted performance outcomes at the end of 10 years, and its economic benefits expressed as social cost savings. These candidates are defined in chapter 3.

- Ending condition: Forecast of the *%Good* and *%Poor* condition measures at the end of the program horizon if no do-something investment candidate is selected in any of the years of the analysis. This condition results from uninterrupted deterioration.

- Work area: Macro in the spreadsheet file that considers each year or budget cycle in the TAMP program horizon, using formulas in these columns to compute the BCR, considering any objective or subnetwork weights specified on the targets worksheet.

- Results: Macro in the spreadsheet file that prioritizes the investment candidates within the budget constraint and places the resulting selections in this section.

- Parameters: Data to assist the worksheet formulas in their calculations to locate the relevant data for each program year or budget cycle. These parameters make it easier for agencies to insert or delete budget cycle periods if more or fewer than 10 are desired.

The list of investment candidates for each program year is independent of the other program years and assumes that no work is done in other years of the program. Thus, assets commonly have a do-something investment candidate identified in every program year in the investment candidate file. Only one of these investment candidates will be selected by the cross-asset tradeoff analysis in each row of the worksheet. Because of deterioration and traffic growth, it is common for costs and benefits to increase from year to year across each row of the worksheet.

The asset identification, current performance, investment candidate, and ending condition sections of the worksheet are meant to be computed in separate systems, such as an agency's PMS and BMS. The research team concluded from this study that these systems can be modified to add a file export capability to output data for assets and investment candidates in this format. These data will then be ready to use in cross-asset decision support tools, such as the TA-MAPO tool.

The TA-MAPO tool is designed to focus on investments that happen just once within any 10-year period and consider just one selected treatment for each asset in any given year. By adopting an incremental benefit-cost approach, it is possible to modify the worksheet to consider additional possibilities, such as up-scoping or adding a second intervention within the program horizon. That exercise is left to the reader.

Table 6 (in chapter 4) defines each column of the asset identification, current performance, and ending condition sections of the investment candidate file. Table 7 defines the columns that are computed by the assets worksheet rather than imported from other systems. Columns in the work area section (Prioritization Cost through Prioritization Rank) pertain to the period indicated at the top of the section. A macro cycles through each of the periods and records the selected investment candidates in the results section.

Table 72. Output data columns computed by the TA-MAPO tool for each row of the assets worksheet.

Column	Definition
Prioritization Cost	Initial cost of the selected treatment (in thousands of dollars).
Prioritization Long-Term Agency Savings Benefit ($000)	Long-term agency cost savings (in thousands of dollars) for period 1.
Prioritization Safety Savings ($000)	Long-term user cost savings allocated to safety (in thousands of dollars). User cost savings from period 1 are allocated to safety or mobility based on which type of performance is improved by the proposed work.
Prioritization Mobility Savings ($000)	Long-term user cost savings allocated to mobility (in thousands of dollars). User cost savings from period 1 are allocated to safety or mobility based on which type of performance is improved by the proposed work.
Prioritization Benefit Weight Long-Term Cost	Weight given to agency benefits for each asset, as specified in the targets worksheet; 1.0 if unweighted.
Prioritization Benefit Weight Safety	Weight given to safety benefits for each asset, as specified in the targets worksheet; 1.0 if unweighted.
Prioritization Benefit Weight Mobility	Weight given to mobility benefits for each asset, as specified in the targets worksheet; 1.0 if unweighted.
Prioritization Benefit ($000)	Total weighted benefit (in thousands of dollars).
Prioritization Benefit Cost Ratio	BCR.
Prioritization Rank	Rank of each asset within the full list. Number 1 is the row that has the highest BCR.
Results Period	Period in which the asset was selected by the tradeoff analysis algorithm.
Results Treatment Category	Treatment selected for the asset in the selected period.
Results Cost ($000)	Initial cost of the selected investment candidate (in thousands of dollars).
Results Condition *%Good*	Forecast condition outcome *%Good*.
Results Condition *%Poor*	Forecast condition outcome *%Poor*.
Results Safety *%Sufficient*	Forecast safety outcome *%Sufficient*.
Results Mobility *%Sufficient*	Forecast mobility outcome *%Sufficient*.

TARGETS WORKSHEET

The targets worksheet within the TA-MAPO tool summarizes asset condition and performance for selected subsets of the network; table 73 and figure 18 provide examples of the worksheet and its associated graph. Each bar in the graph corresponds to one row of the worksheet. Each row pertains to one asset class and one subset of the network, as specified in the first six columns. Agencies can customize the worksheet and graph by adding or removing rows, specifying the subnetwork for each row, and giving each row a name in the "Subnetwork name" column.

The formulas in the current performance and ending performance sections of the target worksheet summarize data from the assets worksheet. Condition and performance measures are weighted by the size column (lane-miles for pavements and deck square feet for bridges).

Targets can be entered for *Condition %Good*, *Condition %Poor*, *Safety %Sufficient*, and *Mobility %Sufficient*. If any of the targets are not satisfied, their cells turn red. Condition targets are shown as diamonds in the graph, and ending conditions as bars: Green for *%Good* is seen in the top of the graph, and red for *%Poor* is seen in the bottom of the graph.

If a portion of the network fails to meet its target, the benefit weighting section can be used to modify outcome performance. Adding weight to long-term agency cost tends to improve condition; meanwhile, adding weight to safety or mobility tends to improve those measures. For example, table 74 shows that pavements in District 1 did not satisfy their target of 15-percent Poor, so 20-percent additional weight was given to agency cost in that portion of the network to attempt to improve its performance.

The effect of the added weight is to multiply long-term agency cost savings by a factor of 1.2 for all pavements in District 1. If the added weight is not enough to reach the target (as in the example), more weight can be added. Each time the weight is changed, all projects are reprioritized. This reprioritization can cause additional investment candidates to be selected in the portion of the network that receives extra weight, which is what improves its performance. Weight can also be negative, which will reduce the performance of a part of the network. Multiple parts of the network can be assigned different weights, but this practice should be used sparingly, as the combined effect of multiple adjustments can sometimes be counterintuitive.

Table 73. Tabular example of the targets worksheet.

Asset Class	NHS	Interstate	SHS	District	Subnetwork Name	Current Size	Current Replacement Value ($)	Current *%Good*	Current *%Poor*	Current Safety *%Sufficient*	Current Mobility *%Sufficient*	Target *%Good*	Target *%Fair*	Target *%Poor*
Pavement	Yes	Yes	All	All	Pavement–Interstate	2,762.32	2,180,689	93.1	0.7	100	100	20	75	5
Pavement	Yes	No	All	All	Pavement–Other NHS	15,444.55	11,569,002	86.7	2.6	100	100	20	65	15
Pavement	All	All	Yes	All	Pavement–SHS	18,212.93	13,754,363	87.7	2.3	100	100	20	65	15
Bridge	Yes	All	All	All	Bridge–NHS	6,784,424	4,070,654	23.9	2.6	86.5	96.6	20	75	5
Bridge	All	All	Yes	All	Bridge–SHS	11,449,232	6,869,539	24.5	3.1	84.9	97.1	20	75	5
Pavement	All	All	Yes	1	Pavement–District 1	4,755.02	3,613,784	90.7	0.8	100	100	20	65	15
Pavement	All	All	Yes	2	Pavement–District 2	4,785.14	3,602,053	86.1	4.0	100	100	20	65	15
Pavement	All	All	Yes	3	Pavement–District 3	4,817.91	3,675,098	82.5	3.7	100	100	20	65	15
Pavement	All	All	Yes	4	Pavement–District 4	3,854.87	2,863,427	92.5	0.5	100	100	20	65	15

Pavement size is in lane-miles; bridge size is in square feet of deck.
Cond. = condition; dist. = district; pvt. = pavement; suff. = sufficient.

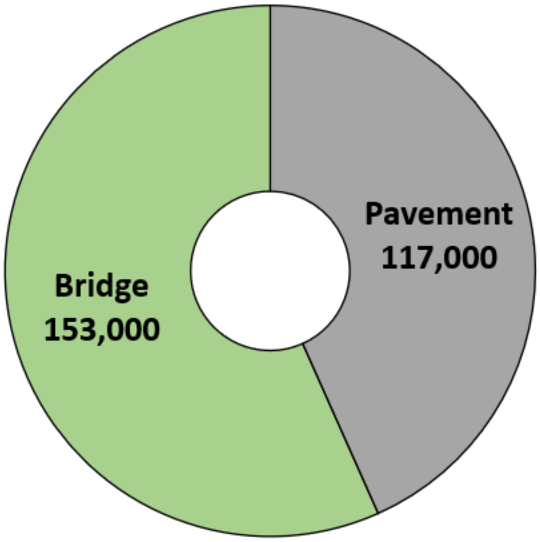
Table 74. Adding weight to a portion of the network in the targets worksheet.

Asset Class	Subnetwork name	Target *%Good*	Target *%Fair*	Target *%Poor*	Target Safety *%Sufficient*	Target Mobility *%Sufficient*	Benefit Weighting Adjusted LT Cost (±%)	Benefit Weighting Adjusted Safety (±%)	Benefit Weighting Adjusted Mobility (±%)	Ending Performance *%Good*	Ending Performance *%Fair*	Ending Performance *%Poor*	Ending Performance Safety *%Sufficient*	Ending Performance Mobility *%Sufficient*
Pavement	Pavement–Interstate	20	75	5	—	—	—	—	—	90.2	6.2	3.5	100	100
Pavement	Pavement–Other NHS	20	65	15	—	—	—	—	—	61.8	23.2	15	100	100
Pavement	Pavement–SHS	20	65	15	—	—	—	—	—	66.1	20.6	13.3	100	100
Bridge	Bridge–NHS	20	75	5	—	—	—	—	—	34	63	3	86.5	96.7
Bridge	Bridge–SHS	20	75	5	—	—	—	—	—	37.7	57.3	5	85.4	97.4
Pavement	Pavement–District 1	20	65	15	—	—	20	—	—	56.8	25.2	18	100	100
Pavement	Pavement–District 2	20	65	15	—	—	—	—	—	68.4	19	12.5	100	100
Pavement	Pavement–District 3	20	65	15	—	—	—	—	—	67.7	20.6	11.7	100	100
Pavement	Pavement–District 4	20	65	15	—	—	—	—	—	72.7	17.1	10.3	100	100

—No data.

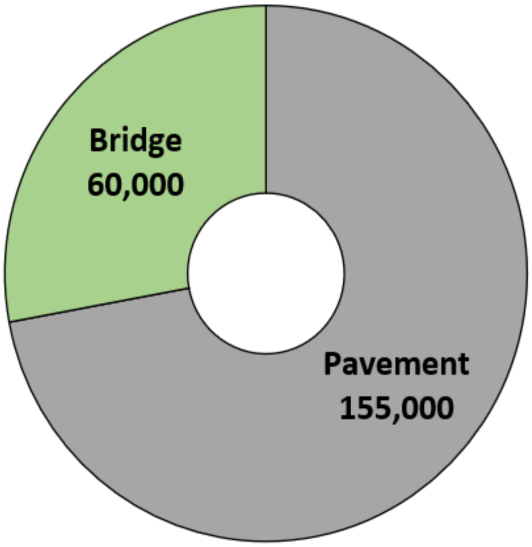
FUNDING ALLOCATION WORKSHEET

The funding allocation worksheet includes a table of subnetworks similar to the targets worksheet, but it does not necessarily have to show the same subnetworks. The worksheet has graphs that focus on the allocation of funding (figure 58) and the corresponding changes in condition (figure 59). The worksheet reports annual spending for each subnetwork and the share of spending devoted to preservation. As with the targets worksheet, the charts and graphs can be customized by each agency to focus on topics of interest.



Source: FHWA.

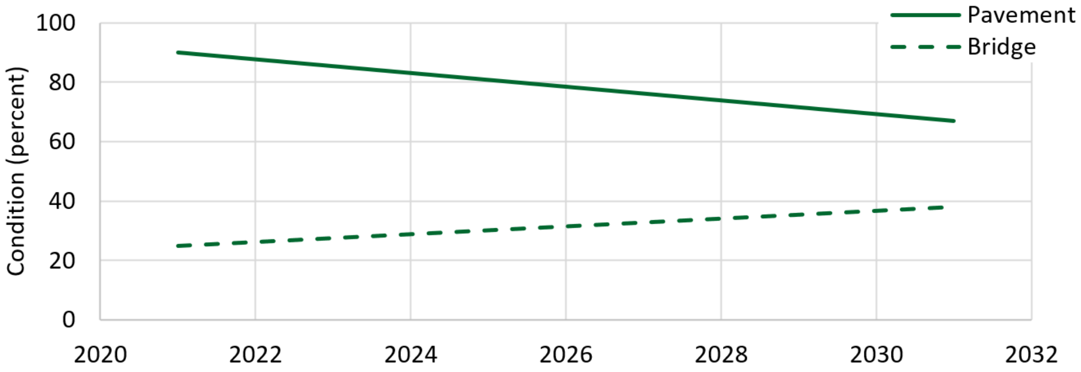
A. 2021 funding allocations.



Source: FHWA.

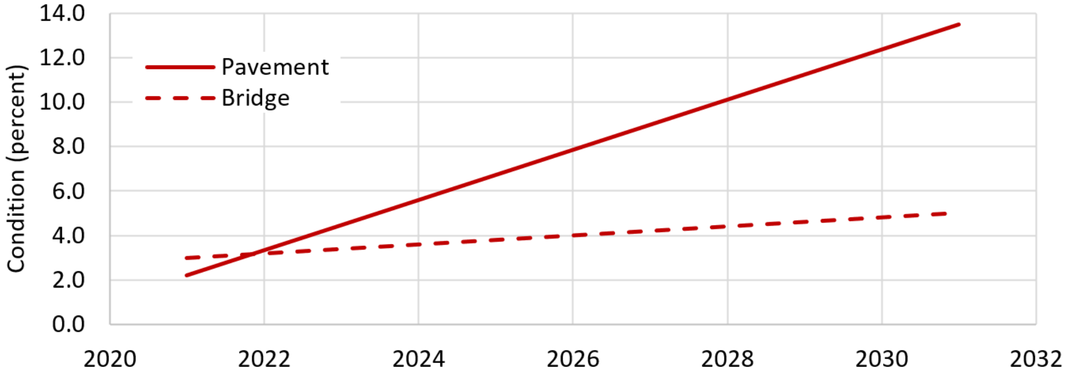
B. 10-year average funding allocations

Figure 58. Graphs. Funding allocation example outputs (thousands of dollars per year).



Source: FHWA.

A. Changes in *%Good* conditions.



Source: FHWA.

B. Changes in *%Poor* conditions.

Figure 59. Graphs. Changes in condition over time for a given funding allocation.

The condition graph merely draws a straight line from current to ending condition, as there is no deterioration model in the TA-MAPO tool to generate more detail. The allocations among subnetworks and the resulting conditions can be highly uneven from year to year as various projects are implemented across the network.

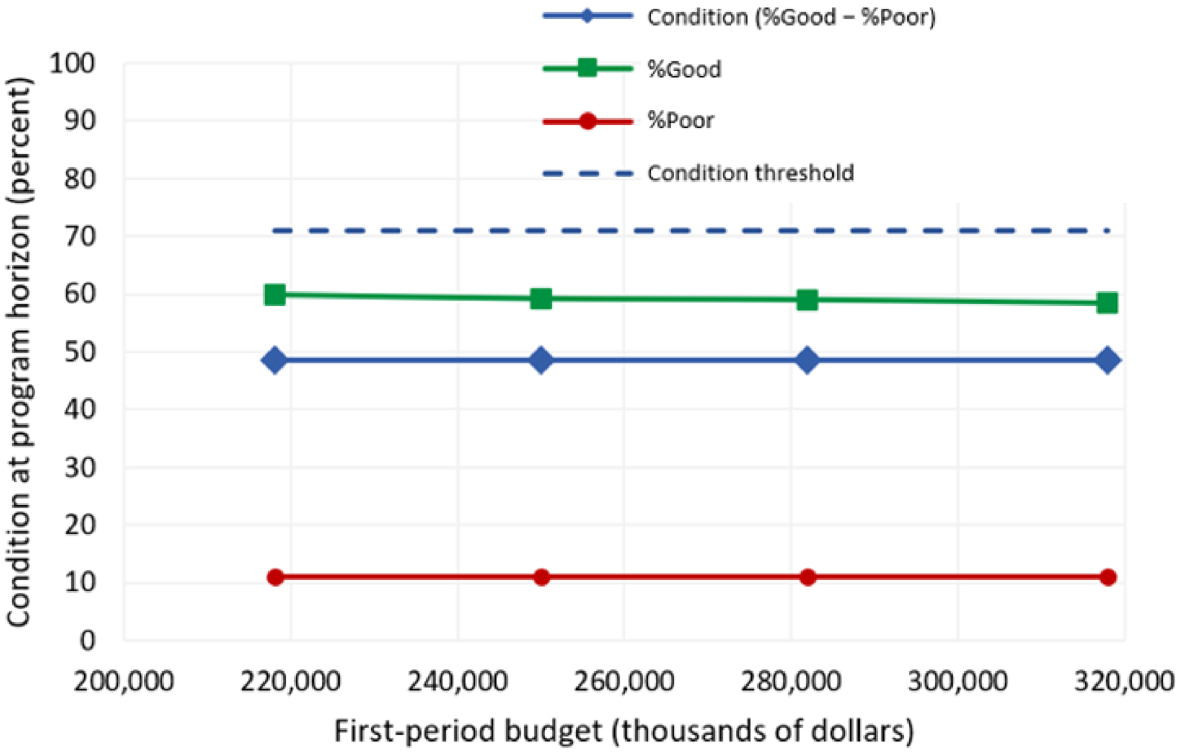
FUNDING ALTERNATIVES WORKSHEET

The funding alternatives worksheet contains spreadsheets and graphs to investigate the effects of alternative funding levels for parts of the network (table 75 and figure 60). The spreadsheets use formulas to generate the funding alternatives, but these budget levels can also be entered manually. More rows can be added, as many as needed. The worksheet is initially set up to provide two separate charts for the NHS and the SHS, but the program's cut/copy/paste features can be used to add more charts and graphs, or fewer, to fit the agency's needs.

A macro is used to apply each funding alternative found in each chart and reprioritize the network. The macro uses the iteration work area table at the bottom of the worksheet to hold intermediate results.

Table 75. Setting alternative funding levels.

Alternative	First Period Budget (million dollars)		Forecasted 10-Year Outcomes					10-Year Period	Period 1
		Current Condition, *%Good -%Poor*	Condition, *%Good - %Poor*	Condition, *%Good*	Condition, *%Poor*	Safety, *%Sufficient*	Mobility, *%Sufficient*	Total Inflated Cost (billion dollars)	Marginal BCR
1	217	71.2	48.2	59.04	10.84	96.92	99.25	2.17	0.13
2	250	71.2	48.23	58.99	10.76	96.92	99.25	2.50	0.11
3	284	71.2	47.71	58.74	11.03	96.92	99.25	2.84	0.1
4	317	71.2	47.46	58.64	11.18	96.92	99.25	3.17	0.09



Source: FHWA.

Figure 60. Graph. Changes in condition over time for a given funding level.

IMPLEMENTATION CONSIDERATIONS

From the experiences of the research team in the pilot testing studies, a few points are especially worthy of emphasis when preparing investment candidate data for the TA-MAPO. These points include the following:

- The benefit-cost performance measure described in chapter 3 may be different from the measure that the existing management systems are using for prioritization. Certain assumptions that are adequate within just one asset class may be invalid when developing a performance measure that is consistent across asset classes.

- Fully modeling the benefits of the investment candidates is important, especially user cost savings from pavement work, which often are neglected (or taken for granted) in PMSs. No cross-asset analysis can serve its intended purpose if it does not fully model the benefits of investment candidates.

- The TA-MAPO tool analyzes the benefit of an investment candidate to be just 1 year of social cost savings, associated with a decision not to delay the project for a year. This number is small compared to total long-term cost savings and is normally smaller than the initial cost of the project. Thus, BCRs are generally less than one but greater than zero.

- It may be helpful for management system developers to review existing tools with cross-asset tradeoff analysis capability, such as HERS, to fully understand the needs of this type of tool (FHWA 2005).

- The scale of the investment candidate file should be consistent with the fiscal scenarios under consideration. In particular, an optimistic fiscal scenario can be modeled in the TA-MAPO tool only if the investment candidate file contains a sufficient number and cost of investment candidates to spend that much money cost-effectively.

- It is important that the investment candidate file contain enough candidates with positive BCRs to spend the anticipated level of funding, and that the candidates provide enough improvement in condition to achieve the expected performance outcomes.

The TA-MAPO depends on the ability of the separate management systems to produce reasonable programs and tradeoffs within their asset classes. For example, the PMS should be able to effectively model optimistic and pessimistic fiscal scenarios for pavements and produce appropriate investment candidates and performance outcomes for these candidates. The investment candidates that are sufficiently cost-effective to be selected by the management system should have positive BCRs when performance measures for the TA-MAPO are calculated, even if the methodology is different than what the management system uses internally.

ACKNOWLEDGEMENTS

The map depicted in figure 8 is taken from MapChart (https://www.mapchart.net/index.html) and was modified by FHWA to indicate the basis on which the States were considered as candidates for the study described in this report.

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