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SYSTEMATICS

Consequences of Delayed Maintenance

NCHRP 14-20

interim report

TRANSPORTATION RESEARCH BOARD
NAS-NRC
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prepared for

National Cooperative Highway Research Board

prepared by

Cambridge Systematics, Inc.

with

Applied Research Associates, Inc.
Spy Pond Partners

September 2011

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1.0 Introduction

1.1 Objectives

The objectives of Phase I of National Cooperative Highway Research Program (NCHRP) project 14-20 are: 1) to summarize the literature on analytical tools for bridge and pavement asset management, the known costs of delayed maintenance, and the risks associated with delaying maintenance; 2) to develop prototype tools to quantify the costs of delayed maintenance actions on pavement and bridges; 3) to illustrate the application of the prototype tools to estimate the cost of delayed maintenance on pavement and bridges; and 4) to summarize other consequences of delayed maintenance not readily incorporated into the prototype tools.

1.2 Audience

The audience for NCHRP 14-20 is state pavement and bridge engineers who need to understand the consequences of delayed maintenance and effectively communicate them to executive decision makers. Two prototype tools, one each for bridge and pavement, were developed for this effort. The tools automate the application of new approaches for estimating the costs of delayed maintenance at a sketch-planning level. Sketch level results often provide sufficient detail for executive level understanding of a finely detailed problem. The tools are simplified versions of larger systems that have been built on a foundation of rigorous econometric, economic, and engineering mathematics, but the tools themselves are easy to use and provide basic, but focused, estimates of the costs of delayed maintenance. These costs are designed to provide decision makers with information needed to understand the implications of potential budgetary decisions and to make policy-level decisions about maintenance funding levels.

1.3 The State of Highway Maintenance Needs and Funding

The United States' highway system has mobilized Americans and facilitated unparalleled economic growth. The Interstate system is now over 50 years old, and in many states other infrastructure is even older. Sufficient and timely bridge and pavement system maintenance provides critical support to the basic goals that transportation agencies typically set for the highway system. Delaying maintenance on the nation's transportation system has the potential to create mobility, safety, and economic challenges and increase transportation agency

costs over the long term. Agencies increasingly have to deal with three bellwether trends while making critical decisions about maintenance funding:

- **Infrastructure in the U.S. is aging and deteriorating.** *Transportation for Tomorrow,* the final report of the National Surface Transportation Policy and Revenue Study Commission, highlights that much of the Nation's highway network was built before the Second World War.[1] National Bridge Inventory (NBI) data indicate that the majority of bridges are over 40 years old.[2] The American Society of Civil Engineers *Report Card for America's Infrastructure* gives America's roads a D-grade.[3] They estimate that it could cost $930 billion to improve the roads, but existing funding covers only half of the need, leaving a $550 billion shortfall in the next 5 years. *Transportation for Tomorrow* states that 13 percent of all bridges in the U.S. are structurally deficient and 1 out of every 7 miles traveled (15 percent) is on pavement ranked "not acceptable" by the Highway Performance Monitoring System. Under current funding levels, more than 40 percent of the miles traveled could be categorized as "not acceptable" by 2055. A TRIP report finds that, about 32 percent of major urban roads are in substandard or poor condition and cost the average motorist $324 in vehicle operating costs.[4]
- **Budgets are expected to remain tight and the buying power of a mile driven is expected to decline**. The major backlog of work described above is indicative of a historic disconnect between preservation needs and funding availability. The current economic environment in the U.S. has further tightened budgets. Americans are driving less[5] and purchasing more fuel-efficient vehicles,[6] reducing revenue for transportation investments. And while fewer vehicle miles of travel (VMT) means less impact on the roadways, the backlog of maintenance and preservation needs can make it challenging to catch up. Even with economic recovery, revenues are likely to

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[1] National Surface Transportation Policy and Revenue Study Commission, *Transportation for Tomorrow: Report to National Surface Transportation Policy and Revenue Study Commission,* December 2007.

[2] National Bridge Inventory ASCII Files, 2010.

[3] American Society of Civil Engineers, *Report Card for America's Infrastructure 2009,* March 5, 2009.

[4] The Road Information Project (TRIP), Key Facts About America's Road and Bridge Conditions and Federal Funding, May 2011.

[5] Total VMT peaked in 2007, declined in 2008, and grew marginally in 2009. Source: table *National Transportation Statistics* 1-36: Roadway Vehicle-Miles Traveled (VMT) and VMT per Lane-Mile by Functional Class, Bureau of Transportation Statistics, updated April 2011.

[6] National Highway Traffic Safety Administration, Summary of Fuel Economy Performance (Public Version), April 20, 2010.

remain constrained. New federal rules require vehicles made in 2016 to have an average fuel economy of 35.5 miles per gallon (mpg), a significant increase from the 2010 new vehicle fuel economy (27.5 mpg).[7] The fuel economy standards support national goals to reduce greenhouse gas emissions, but will reduce gas tax revenues per mile driven. At the same time, construction costs continue to increase[8] while the federal gas tax remains at 1993 levels. Also, fuel prices are expected to climb.[9] Observed trends during the recent recession demonstrated that drivers tend to reduce how much they travel when gas prices hit four dollars.[10] Less driving reduces expected revenue. While solutions to these challenges – such as VMT-based fees – have been discussed and debated, there is no indication that these will be considered in the short term. Finally, these pressures cause a decrease in revenue and the highway trust fund has been running a negative balance since 2008 and is projected to do so into the future. Figure 1.1 summarizes the discrepancy between spending outlay and receipts from 2004 through 2010 and predicts the continued discrepancy over the coming five years.[11]

[7] National Highway Traffic Safety Administration, Summary of Fuel Economy Performance (Public Version), April 20, 2010.

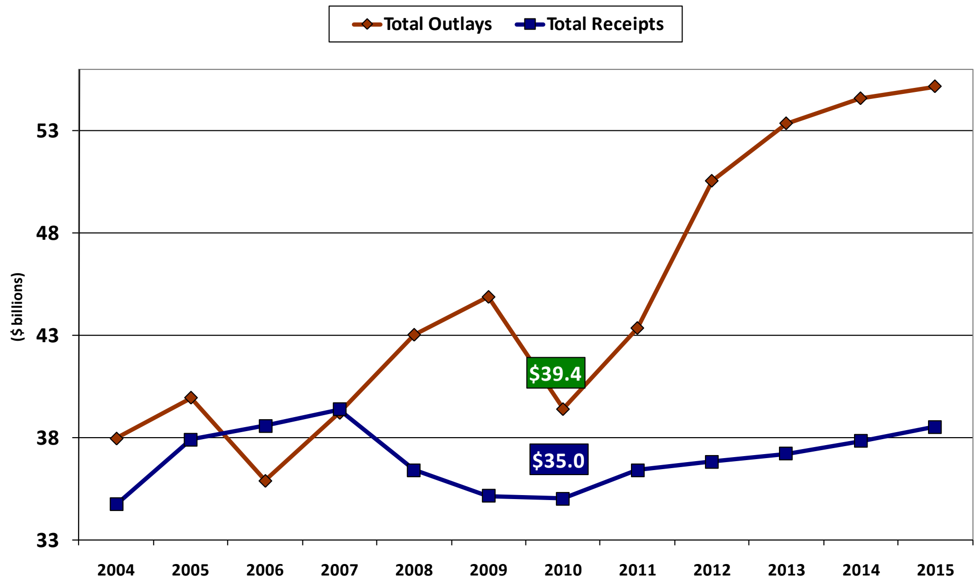
[8] The Producer Price Index (PPI) for Material and Supply Inputs to Highway and Street Construction has increased from 133.7 in 2002 to 205.3 in 2009. Source: Bureau of Labor Statistics, http://data.bls.gov/timeseries/NDUBHWY--BHWY-- (accessed August 16, 2011).

[9] The Energy Information Administration estimates that, fuel prices will increase by 40 percent by 201 or nearly $4 per gallon. Source: Calculated using the average fuel price as of October 16, 2010 from American Automobile Association, Daily Fuel Gauge Report, and the Energy Information Administration reference case energy cost for 2016 ($2.83 X 1.4).

[10] Consumer Reports, "Gas prices survey shows pain at the pump hurts at home," June 2008; http://www.consumerreports.org/cro/cars/new-cars/resource-center/gas-prices-survey/overview/gas-prices-survey.htm.

[11] American Association of State Highway Transportation Officials, "Surface Transportation Authorization – The Big Picture and Legislative Update," Presented to the Northeast Association of State Highway Transportation Officials, 2011.

Figure 1.1 Highway Trust Fund: Receipts and Outlays Discrepancy



Note: Excludes $8.017 billion transfer from General Fund to Highway Account of HTF in September 2008; $7 billion transfer from General Fund to Highway Account of HTF in August 2009; $19.5 billion transfer from General Fund to Highway and Mass Transit Accounts of HTF in March 2010.

Source: AASTHO, "Surface Transportation Authorization – The Big Picture and Legislative Update," Presented to the Northeast Association of State Highway Transportation Officials, 2011.

- **Growing travel demand is expected to increase highway system wear and tear**. While current economic challenges are causing individuals choose to drive less and buy more fuel-efficient vehicles, economic recovery and population growth could bring increased freight[12] and personal[13] travel. Increased freight travel, bringing heavy loads onto the nation's highways, will have the most significant impact on the condition of the system.

1.4 Understanding the Consequences of Delayed Maintenance

How Agencies Delay Maintenance

Due to the compounding pressures of aging infrastructure, increased demand, and decreasing revenues, transportation agencies are increasing being forced to

[12] Estimates indicate that freight tonnage will continue to increase at 1.6 percent per year, growing 61 percent between 2010 and 2040. Source: Federal Highway Administration, Freight Analysis Framework, 2011.

[13] Estimates indicate that VMT will continue to grow at a rate of one to two percent per year. Source: AASHTO, *The Bottom Line Report*, 2009.

think critically about how to operate in an environment in which needs significantly outweigh resources. Following are some of the options for maintenance departments as they seek to address resource constraints:

- **Perform no maintenance**. Under the most severe budgetary pressures, an agency might choose to simply stop maintaining existing infrastructure for some duration. Stopping all maintenance would allow deterioration to advance unchecked, and, eventually, resulting in the entire system reaching a state of disrepair. Compared to maintained highways, unmaintained highways are more likely to lead to increased safety problems, decreased travel speeds, greater wear and tear on vehicles, higher costs for consumers, increased business costs by reducing just in time efficacy, increased fuel consumption, reduced air quality, and increased agency life-cycle costs.
- **Perform only inexpensive maintenance activities**. Agencies could decide to patch over bigger problems in lieu of performing less expensive, but appropriate, maintenance actions. For example, agencies could opt to perform light resurfacing to improve the smoothness of the road in the short term instead of performing more fiscally intensive preservation actions like milling and resurfacing. Light resurfacing on a substrate in disrepair is like laying new shingles on a rotting roof; the maintenance "papers" over real problems and those root problems continue to grow over time. Unfixed root problems can grow and eventually require more expensive activities then would have otherwise been necessary.
- **Maintain only priority assets**. Under budgetary pressures, agencies might focus limited maintenance resources on key roadways and bridges, such as interstate highways or highways critical for freight movement. By maintaining priority assets, agencies could support areas with significant mobility needs, but might allow other areas to fall into disrepair more quickly by comparison.
- **Perform maintain only in reaction to failed infrastructure.** Agencies could focus maintenance resources on bridges and pavements that have fallen into a state of disrepair that can no longer be ignored. Performing work on failed infrastructure is essential because failing to do so could lead to hazardous safety issues that could put the traveling public at risk. Agencies and users would experience significant cost increases if agencies work solely reactively to fix failed infrastructure. Infrastructure failure can happen at any time, including during rush hour, and must be fixed immediately, often increasing the overall cost of maintenance. Furthermore from a life cycle perspective, it is often more expensive to replace an asset sooner than to extend its life further through preventive maintenance.

The most likely scenario for agencies for agencies forced to consider delayed maintenance is to mix and match some of the options described above, maintain a mix of assets and applying a mix of fixes. For example, they could maintain some assets in good condition and some in poor condition in an attempt to

maintain a reasonable overall average condition, do inexpensive maintenance when possible while keeping long term expenses low and keeping assets from failure as much as possible. They might maintain important assets and move to other assets as resources allow. This mixed approach is more representative of how agencies might maintain their system than the strict approaches described above.

Example Narrative of Delayed Maintenance

Following is a fictitious story of what could happen when bridge maintenance is delayed. It illustrates one potential narrative of the consequences of delaying maintenance. A similar story could be told for pavements or any other asset. The principles remain the same.

Imagine transportation agency that has been maintaining its bridge network of bridges with appropriate maintenance actions. The state's bridges are aging, but they are otherwise in a good state of repair, requiring a typical mix of scheduled and unscheduled maintenance activities.

The agency anticipates that federal bridge funds will either be consistent with the last two years, without accommodating for the increase in construction costs they have recently experienced, or be cut by up to 25 percent. There also is no immediate plan to increase state gas taxes or to implement new forms of revenue. Regardless of the final federal budgets, the agency expects its bridge maintenance budget to decrease relative to previous years.

The agency decides to refocus its efforts toward maintaining the critical bridges carrying the most freight and daily travel, in an attempt to continue to support statewide economic growth, safety, and mobility goals. On all other bridges, the agency uses remaining funding to perform light maintenance actions and, otherwise, replace failed elements or bridges.

Several years pass and transportation revenue has not yet increased and the agency is forced to continue the policy of maintaining critical assets and doing the bare minimum on all other assets. Due to lack of maintenance, the non-critical bridges eventually reach a point where they begin to deteriorate rapidly. Proper maintenance that would include painting and patching of steel beams and concrete decks is eliminated and, instead, the agency begins to place plywood or netting under bridge decks to catch falling pieces of concrete and protect passersby. Inspectors find evidence of corroded beams and decks with extensive cracking.

One bridge in the south district abruptly develops a gaping hole in the deck that needs to be fixed immediately before the bridge can be opened to the traveling public, causing commuters to travel 10 miles out of their way. The gaping hole needs to be filled and the impromptu work costs extra in labor and materials. Smaller holes begin to open and concrete chunks begin to fall from underneath the bridge decks throughout the state, necessitating immediate and expensive replacement. The agency has moved from proactive maintenance on its non-

critical assets to a harried pace of reactive maintenance and it is costing additional money. After years of neglect, the bridges are in disrepair. It will take a significant outlay of funds to perform appropriate maintenance on these bridges and significant continued funding to restore the network back to the condition it would have been in if maintenance were not delayed.

Communicating the Consequences of Delayed Maintenance

Many maintenance activities are designed to deter and impede asset deterioration. Therefore, delaying these activities can cause assets to deteriorate more quickly over time. This is the core impact of delayed maintenance, and the main driver of several consequences, including:

- **Increased long term agency costs**. Delaying maintenance can require agencies to perform more extensive and expensive maintenance actions earlier than they otherwise would have. The extensive work can increase an asset's life cycle cost.
- **Increased user costs.** Bridges and roads keep our economy moving by keeping goods and people connected. A poorly maintained system will eventually experience a rapid decline in the level of service it provides. Under normal circumstances, detouring around closed bridges and driving over bridges in poor condition increases the cost of driving through increased wear and tear on vehicles, travel time, and fuel cost. If a section of highway needs major repairs, agencies close the road, close sidewalks, reduce the total number of lanes, and, at times, impose weight-restrictions, all of which can reduce capacity of the roadway, increases congestion and delay, and make travel less reliable. This slows the delivery of goods, commute times, impacts people visiting family, and visitors visiting special destinations. Impacting connectivity has a negative impact on the economy.
- **Increased risk of failure during catastrophic events.** Infrastructure in disrepair potentially is less structurally sound and could fail more readily when catastrophic events occur. For example, a bridge with a crumbling concrete deck has a worse chance of surviving a significant weather event than a well maintained bridge.
- **Increased risk of failure under normal conditions.** Bridges are more likely to fail under normal conditions when they are not properly maintained. Poorly maintained pavements and bridges increase safety risks for drivers, potentially increasing the economic cost of lost lives.
- **Decreased safety.** Roads and bridges in disrepair can provide a rougher traveling surface, which can increase the chances of a driver losing control of

their vehicles and crashing.[14] Rougher roadways can increase vibration exposure to drivers and pose health risks. More deformed roadway edges can cause drivers to lose control.

- **Loss of public support for transportation agencies.** As the level of service declines and user costs increase, users could eventually lose faith in an agency's ability to effectively manage its infrastructure and budget. Arguments to increase revenue might be less likely to succeed if this trust and support fades, which could make it more difficult to capture needed revenue for improved maintenance in the future, and thereby introduce a self reinforcing feedback loop.

1.5 FOCUS OF THIS REPORT

While the real consequences to delaying maintenance are generally understood there has been relatively little research quantifying the real costs or other non-quantifiable consequences. In spite of the shared understanding that delaying maintenance is undesirable, transportation agencies often find themselves in a position where they must delay maintenance. They are no longer determining *whether* they will delay maintenance but *how much* they will have to cut, *how long* they will have to cut it for, and *from what programs* they will have to cut it from to make cuts to minimize negative consequences. Two new sketch planning level tools were developed as part of NCHRP 14-20 to address this gap and enable agencies to determine and communicate the real costs of delayed maintenance.

Phase I of the project developed a process for quantifying the costs of delaying maintenance actions for pavement and bridge assets, leveraging existing tools and data to facilitate the analysis. The remainder of this interim report presents the findings from Phase I. It is organized as follows:

- **2.0 Framework for the Analysis.** This section describes the overall approach to quantifying the costs of delayed bridge and pavement. More detailed approaches are provide in sections 4.0 and 5.0.
- **3.0 Current State of the Practice.** This section describes the current state of the practice based on literature review findings. The review summarizes current tools used for pavement, bridge, and other asset management; risks associated with delayed maintenance; and findings from other practices regarding delayed maintenance.
- **4.0/5.0 Analyzing the Costs of Delayed Bridge/Pavement Maintenance.** These sections describe detailed approaches for analyzing the costs of delayed bridge (section 4.0) and pavement (section 5.0) maintenance, describe

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[14] ARRB Group, *Relationship between road surface characteristic and crashes on Victorian rural roads,* 2008.

the prototype tools for estimating the costs of delayed maintenance, and describe pilot tests of the methodologies.

- **6.0 Phase II Work Plan.** This section describes the work plan for Phase II of NCHRP 14-20, which will focus on the consequences of delayed maintenance on other, non-bridge and non-pavement infrastructure.

2.0 Framework for Analysis of the Costs of Delayed Maintenance

This section defines a general framework for analyzing the costs of delayed maintenance. More details on the application of this framework for bridges and pavements is provided in following sections. While the framework is consistent across asset types, the details for any given asset can vary significantly based on the data and analytical tools that exist.

The general framework compares agency and user costs accrued over time in one scenario (the baseline or maintenance scenario) to another (the delayed maintenance scenarios). In the baseline scenario, an agency performance "proper" maintenance, which is defined as implementing the recommended treatments (based on an asset's current condition) at the recommended time. In the delayed maintenance scenarios, an agency maintains only the portion of the system that funding allows (*the extent*); performs no maintenance on the remainder of the system, but does replaces failed assets on an as-needed basis (*the maintenance package*); and continues in this manner for as long as the funding is limited (*the duration*). Once the funding is restored, the agency immediately resumes proper maintenance.

In each year of the analysis, the agency will experience a real outlay of funds (construction, labor and materials costs) and the system users will accrue real user costs (increased travel time, vehicle wear and tear, etc.). The difference between the baseline scenario and each delayed maintenance scenario (recorded as net present value) is the cost of delayed maintenance.

This framework enables the development of several delayed maintenance scenarios that show how the duration of maintenance delay and the extent of maintenance delay impact the cost of delayed maintenance. Each delayed maintenance scenario, is defined by the extent of delayed maintenance, the delayed maintenance package, and the duration of delayed maintenance.

- **Extent of delayed maintenance.** The agency maintains only the portion of the system that funding allows and delays maintenance on the remainder of the system until funding is restored. The agency selects a mix of assets in good and poor condition in an attempt to minimize long term cost while attempting to keep the system in a state of good repair. For the analysis, the extent could vary from 0 to 100 percent of the system.

- **Delayed maintenance package.** The agency performs no maintenance but replaces assets when they fail. When funding is restored, the agency performs proper maintenance on the entire system. The maintenance package defines the agency work policy over the analysis period. A work

policy defines a condition level or an asset age at which maintenance work should be performed to minimize long term cost or to maintain a certain level of service. Each action has a user and agency cost.

- **Duration of delayed maintenance.** The agency delays maintenance for as long as the funding is unavailable. For the analysis, the duration varies from 0 to 10 years.

Each scenario can be evaluated using agency-specific **inventory** (i.e. number of girders) and **condition** information.

In summary, the NCHRP 14-20 framework enables agencies to estimate the costs of delayed maintenance based on various combinations of the following variables:

- Inventory;
- Condition;
- Extent of delayed maintenance;
- Maintenance package; and
- Duration of delayed maintenance.

3.0 Literature Review

This section summarizes key findings from the literature review conducted as part of the study. It defines maintenance; summarizes previous studies related to determining the consequences of delayed maintenance, and summarizes available technical approaches and tools for estimating the costs of delayed maintenance for bridges and pavements.

3.1 DEFINING MAINTENANCE

The term "maintenance" often is interpreted differently among state transportation agencies. However, in order to develop an analytical approach for estimating the impacts of delayed maintenance for NCHRP 14-20, a clear, discrete, and unambiguous definition of maintenance is required. This section recommends a definition of maintenance based on accepted national standards.

In general, maintenance and preservation actions are intended to address infrastructure assets while they are still in good or fair condition and before the onset of serious deterioration. Federal law, the American Associations of State Highway and Transportation Officials (AASHTO), and Federal Highway Administration (FHWA) have developed formal definitions of maintenance, while transportation agencies often operate with their own working definition. In these definitions, the concepts of maintenance and preservation are often considered to be interchangeable. While each organization has developed a definition specific to the infrastructure specific to their interest, the definitions of maintenance are generally transferable among all infrastructure. Examples of specific definitions include:

- **US Code Title 23**: "The term 'maintenance' means the preservation of the entire highway, including surface, shoulders, roadsides, structures, and such traffic-control devices as are necessary for safe and efficient utilization of the highway."[15]
- **AASHTO:** "Highway maintenance encompasses a program to preserve and repair a system of roadways with its elements to its designed or accepted configuration and to an accepted quality of performance."[16]
- **FHWA Bridge Preservation Expert Task Group**:[17] The term "bridge preservation" refers to "actions or strategies that prevent, delay or reduce

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[15] U.S. Code Title 23/Chapter 1/Subchapter 1/section 101.

[16] AASHTO, *Maintenance Manual for Roadways and Bridges*, 2007.

deterioration of bridges or bridge elements, restore the function of existing bridges, keep bridges in good condition and extend their useful life. Preservation actions may be preventive or condition-driven.[18]

In addition to these definitions of overall maintenance, AASHTO and FHWA have defined various subsets of maintenance. Examples include:

- **Preventive maintenance** is "a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity)."[19]
- **Routine maintenance** "consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service."[20]
- **Catastrophic maintenance** "describes work activities generally necessary to return a roadway facility back to a minimum level of service while a permanent restoration is being designed and scheduled. Examples of situations requiring catastrophic pavement maintenance activities include concrete pavement blow-ups, road washouts, avalanches, or rockslides."[21]

Existing literature generally defines maintenance as proactive treatments to prolong the useful life of infrastructure. Based on this finding and similarities between the existing definitions presented above, NCHRP 14-20 defines "maintenance" as any maintenance, repair, and rehabilitation (MR&R) activity that an agency performs in advance of infrastructure failure. Delaying these proactive MR&R actions is considered "delaying maintenance." Rebuilding reactively after an infrastructure fails is not considered maintenance.

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[17] The Bridge Preservation Expert Task Group (BPETG) were charged with developing and implementing a clear and consistent bridge preservation terminology. The group is comprised of representatives from AASTHO, FHWA, academia and industry.

[18] FHWA BPETG Working Definition of Bridge Preservation as of October 15, 2010.

[19] AASHTO Standing Committee on Highways, 1997.

[20] AASHTO Highway Subcommittee on Maintenance.

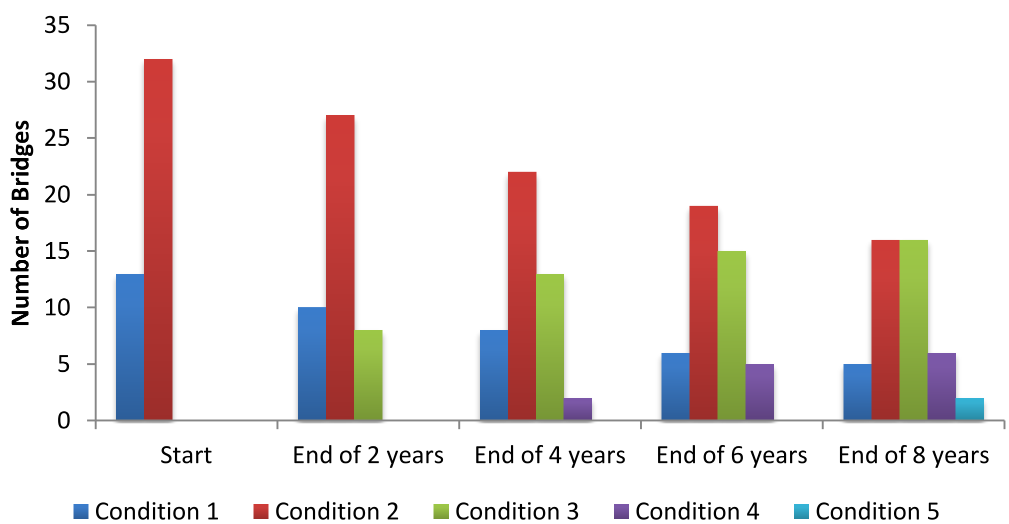
[21] FHWA memorandum on Pavement Preservation Definitions, September 12, 2005.

3.2 ESTIMATING THE COST OF DELAYED MAINTENANCE

There are three basic approaches for communicating the consequences of delayed maintenance: as a qualitative description of what would happen, as a dollar value that represents the change in an agency's cost or its user costs, and as a performance measure that reflects the change in the condition of the assets. This section summarizes existing literature on the costs of delayed maintenance. The study team found very few recent studies that attempt to quantify the costs of delayed maintenance. The two examples that were reviewed are summarized below.

A study conducted in 2002 by the Rhode Island Department of Transportation determined that delaying bridge washing for a period of eight years could cost an agency approximately $20,000 more per bridge to address the deficiencies caused by corrosion. Researchers modified Pontis deterioration models to assess the economic consequence of delaying the washing activity on painted steel open girders on 45 bridges. Figure 3.1 illustrates the deterioration of the bridge network as a result of delaying maintenance for eight years. After eight years it is only cost-effective to wash and clean 21 bridges (i.e., bridges in condition states 1 and 2), the remaining 24 bridges transition to condition states 3, 4, and 5 and require more expensive treatments to address the actions recommended for these conditions. Properly maintained girders remain in their original condition over the eight year period.

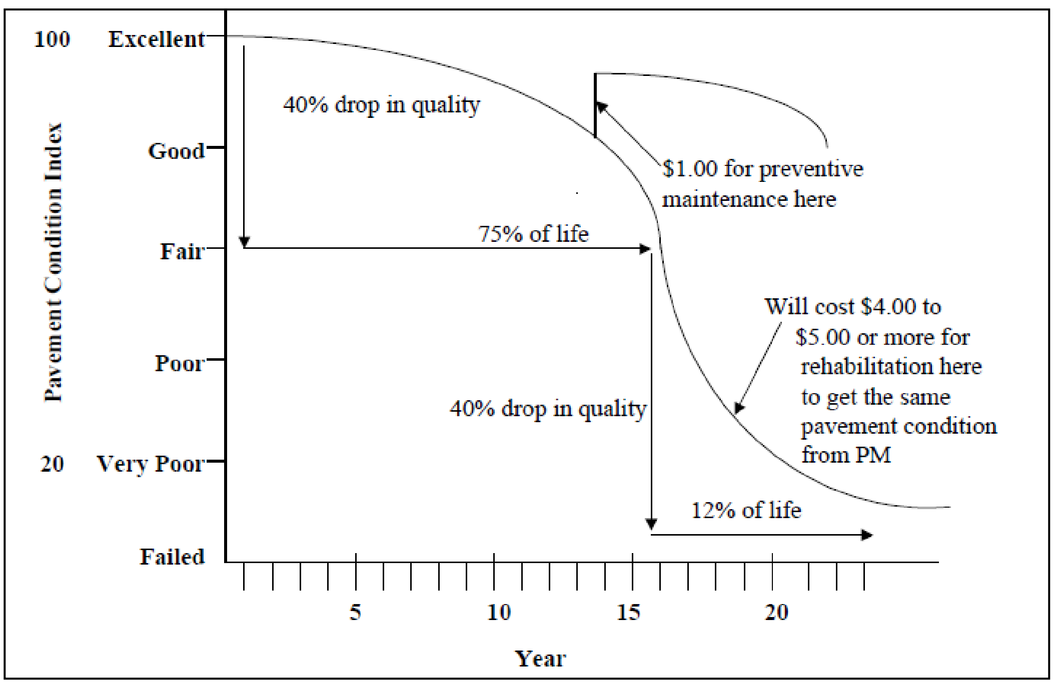
Figure 3.1 Network Consequences of Delaying Bridge-washing Activities



A 2000 study by the Foundation for Pavement Preservation used Figure 3.1 to illustrate the costs of delaying maintenance on pavements using a fabricated deterioration curve and maintenance costs. The study team found delaying

pavement maintenance for four years could cost four to five times more than performing the proper maintenance.[22] In the example illustrated in Figure 3.2, there are two paths that diverge around year 14. The first path shows what happens when maintenance is performed; the pavement deteriorates slowly from excellent condition in year zero to good condition in year 14, at which time a preventative maintenance is performed for $1, and the condition returns to near-excellent condition before continuing to gradually deteriorate. The second path shows what happens maintenance is delayed; the pavement deteriorates from year 0 to year 14 as it did in the first path, but in year 14, maintenance is delayed until year 18. The pavement deteriorates quickly from year 14 to year 18, diminishing from good condition to poor to very poor condition. In year 18, the cost of maintenance is $4 to $5. In this illustrative example, the cost of maintenance is four to five times greater than a baseline scenario.

Figure 3.2 Illustrative Cost of Delayed Pavement Maintenance



Source: Hicks, R.G., S.P. Seeds and D.G. Peshkin, *Selecting a Preventive Maintenance Treatment for Flexible Pavements*, Foundation for Pavement Preservation, Washington DC, 2000.

A 2007 NCHRP synthesis found that, depending on the asset, up to 10 to 15 percent of surveyed states DOT employ "deferred maintenance" approaches on

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22 Hicks, R.G., S.P. Seeds and D.G. Peshkin, *Selecting a Preventive Maintenance Treatment for Flexible Pavements*, Foundation for Pavement Preservation, Washington DC, 2000.

roadside assets.[23] However, the NCHRP 14-20 research team had difficulties finding recent examples of approaches that could be used to understand the consequences of delayed maintenance.

The one study that was located was a 2004 study focused on culverts. The study found that culvert replacement costs were substantially higher when these assets failed than when they were properly maintained and/or replaced before reaching the end of their design life.[24] The study compared the cost to replace a culvert that has been properly maintained to one that has failed. On Interstate 70 in Colorado, for example, the emergency replacement cost of a culvert is 233 times greater than the normal replacement cost of a culvert with a 50-year service life; on Interstate 480 in Ohio, the emergency replacement cost of a culvert is 26 times greater than the normal replacement cost of a culvert with a 50-year service life; and on State Route 173 in Utah, the emergency replacement cost of a culvert is seven times greater than the normal replacement cost of a culvert with a 20-year service life.

3.3 Performance Measures

This section summarizes what measures agencies use to track the performance of bridges, pavements, and other assets. It describes a broad set of performance measures used in practice and recommends specific measures for use in NCHRP 14-20.

Bridge Performance

Performance Measures

Bridge performance measures include element-level health or condition ratings, aggregated bridge and network level health ratings, and the more qualitative structural deficiency status. A summary of the primary performance measures follows:

- **Component condition ratings.** The ratings range from nine (excellent condition) to zero (failed condition) for deck, superstructure, and substructure. The ratings are based on bi-annual field inspections of bridge

[23] Markow, M.J., *Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts and Sidewalks*, NCHRP Synthesis 371, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, 2007.

[24] Perrin, Jr., J. and Jhaveri, C.S., "The Economic Cost of Culvert Failures," Presented at the 83rd Annual Meeting of the Transportation Research Board, 2004.

components. The data are available in the National Bridge Inventory (NBI) file. [25]

- **Element condition ratings.** Element condition ratings are similar to component condition ratings but are tracked at the element level. Element level inspection data are determined through field inspections and made available from some agency Pontis[26] databases, or can be developed using NBI component level data and a converter that synthesizes these data into element-level data.
- **Aggregate Health Index.** A measure that ranks the health of *components, bridges, or networks of bridges* on a continuous 0 to 100 scale. The measure is a weighted aggregate of the element level data. To aggregate the element-level result, weights are assigned to the elements according to the economic consequences of element failure. Thus, elements whose failure has relatively little economic effect, such as railings, receive less weight than elements whose failure could close the bridge, such as girders. [27]
- **Structural Deficiency status.** A rating of four or less on one of the component condition rating items classifies a bridge as structurally deficient.[28] The data are available in the NBI file.
- **Sufficiency rating.** The sufficiency rating is based on the aggregation of four separate factors into a single numeric value ranging from 0 (entirely insufficient or deficient) to 100 (entirely sufficient) that indicates whether a bridge is sufficient to remain in service.[29] The data and aggregate measure are available in the NBI file.

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[25] State DOTs are required to record and submit National Bridge Inventory (NBI) data to the FHWA for all bridges on or over U.S. roads, as well as on culverts greater than 20 feet in length. The NBI dataset contains condition data by bridge component – deck, superstructure, substructure, channel/channel protection, and culvert. Data standards, collection procedures, quality control processes, and calculation methods related to the NBI data set are well established and have been used by state DOTs and the FHWA for several years.

[26] More than 40 states license Pontis and the Pontis database contains all NBI data items, as well as more detailed element-level inspection details.

[27] Thompson, Paul D., and R.W. Sheppard, *AASHTO Commonly-Recognized Bridge Elements: Successful Applications and Lessons Learned*, June 2000.

[28] Bridging the Gap: Restoring The Nation's Bridges, American Association of State Highway transportation Officials, http://www.transportation1.org/bridgereport/struggle.html (Accessed August 10, 2011)

[29] *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges,* FHWA, December 1995.

Recommendations

The audience for the results of NCHRP 14-20 are engineers who need to work with decision makers to understand the consequence of potential funding decisions. This report describes a sketch planning methodology to generate the information required to support these types of discussions. Health index provides a brief, comprehensive, simple to understand measure of the health of the bridge network and can help decision makers to quickly assess the relative impacts of their funding decisions.

Pavement Performance

Performance Measures

Available systems of pavement condition evaluation and monitoring range from State-specific pavement management systems (PMS) to the national Highway Performance Monitoring System (HPMS). Prior to the recent HPMS update, the main measure of pavement condition used in HPMS was International Roughness Index (IRI). In addition to IRI, HPMS 2010+ includes data on rutting, faulting, and cracking. Outside of the HPMS program, State DOTs collect a wide variety of additional pavement data elements, including longitudinal cracking, transverse cracking, fatigue cracking, rutting, and others. Figure 3.2 illustrates the results of a nationwide survey conducted in 2009 reported.[30] The survey also found that all but one of the responding agencies used some form of a composite measure to report on the condition of their pavement network. Overall, there is significant variance between agencies in terms of the specific items collected, data collection protocols, and methods/equipment used to collect data (e.g. manual versus automated methods).

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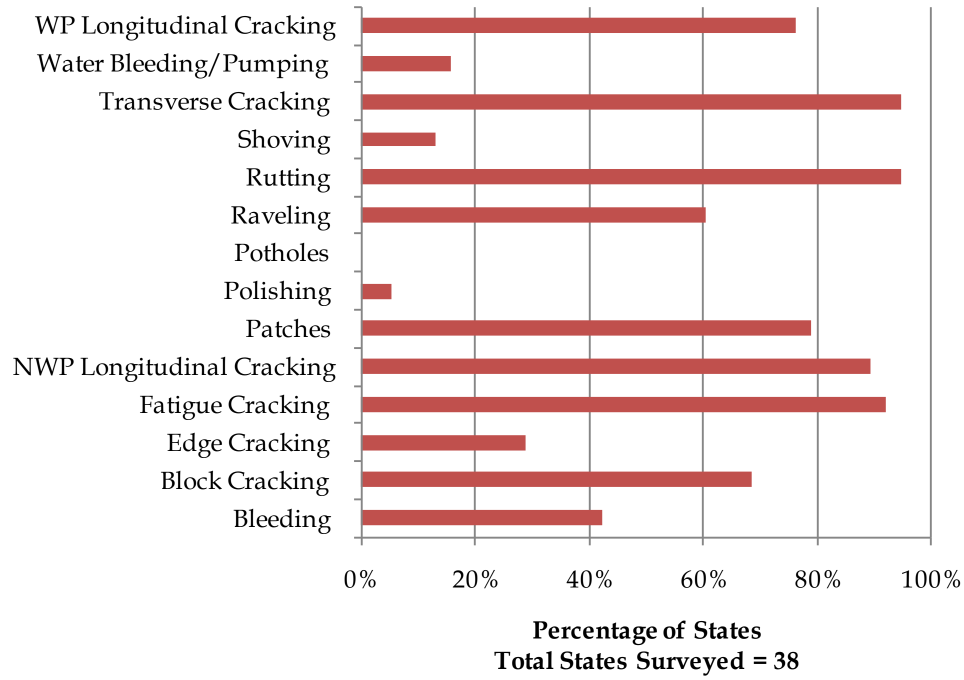
[30] Wolters, A.S. and K.A. Zimmerman, *Research of Current Practices in Pavement Performance Modeling*, Report No. FHWA-PA-2010-007-080307, Pennsylvania Department of Transportation, Harrisburg, PA, 2010.

Figure 3.3 Measures Used for Asphalt Pavement



Source: Research of Current Practices in Pavement Performance Modeling, FHWA-PA-2010-007-080307

Following are few illustrative examples of types of measures used to monitor pavement condition:

International Roughness Index (IRI)/Smoothness. IRI, developed by the World Bank, is a measure of roughness, or, formally, "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality."[31] The common units of measurement are inches/mile. The results range from 0 (smooth) to rough, with rough being open ended and dependant on specific road conditions and speed. Data are available through the Highway Performance Monitoring System (HPMS) dataset and agency pavement management systems. Pavement data collection protocols and analysis for IRI are somewhat consistent, although there is variability among states.

Rutting. Rutting is a measure of surface depression in the wheelpath and tracked in inches.[32] Ranges for the measure vary by agency, but are generally categorized by rutting depth buckets. For example, the measure might range

[31] *Highway Performance Monitoring System Field Manual for the Continuing Analytical and Statistical Database,* FHWA, May 2005.

[32] Rutting, Pavement Interactive. http://pavementinteractive.org/index.php?title=Rutting (Accessed August 11, 2011).

from slight ruts (shallower than a quarter inch) to deep ruts (deeper than a half inch). Pavement data collection protocols and analysis of rutting data are inconsistent among states.

Cracking. Different agencies track different types of cracking. Primary types of cracking include longitudinal cracking (cracking parallel to the pavement centerline[33]), transverse cracking (cracking perpendicular to the pavement centerline[34]), or alligator/fatigue cracking (interconnected cracks caused by traffic fatigue[35]). Agencies generally measure cracking in cracks per mile. Severity of transverse cracking, for example, ranges from zero cracks per mile on the low end to upwards of 50 cracks per mile. Pavement data collection protocols and analysis for cracking are very inconsistent among states.

Pavement condition indices. A composite index can incorporate rideability, pavement distress and structural integrity either directly or indirectly. Highway agencies have adopted their own set of protocols in condition survey practices and defining these indices[36,37,38]. There currently is no uniformity among agency practices in terms of how the define and calculate pavement condition indices.

Pavement remaining service life (RSL). According to FHWA, service life of a new pavement is defined as "the period over which a pavement section adequately performs its desired function or performs to a desired level of service. For an existing pavement, RSL is simply the amount of service life left."[39] While theoretically an understandable and relatively simple measure, RSL suffers from several serious technical issues, including lack of agreement on specific technical

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[33] Longitudinal Cracking, Pavement Interactive. http://pavementinteractive.org/index.php?title=Longitudinal_Cracking (Accessed August 11, 2011)

[34] Transverse Cracking, Pavement Interactive. http://pavementinteractive.org/index.php?title=Transverse_Cracking (Accessed August 11, 2011)

[35] Fatigue Cracking, Pavement Interactive. http://pavementinteractive.org/index.php?title=Fatigue_Cracking (Accessed August 11, 2011)

[36] Pagagiannakis, A., N. Gharaibeh, J. Weissmann and A. Wimsatt, Pavement Score Synthesis, Report No. FHWA/TX-09/0-6386-1, Submitted to the Texas Department of Transportation, Austin, TX, 2009.

[37] Reza, F., K. Boriboonsomsin and S.M. Bazalmit, *Pavement Performance Index*, Report No. ST/SS/05-001, Submitted to the Ohio Department of Transportation, Columbus, OH, 2005.

[38] Wolters, A.S. and K.A. Zimmerman, 2010.

[39] FHWA, *Pavement Health Track (PHT) RSL Forecasting Models: Technical Information*, May 2010.

terms (and even the definition of RSL) between states, lack of consistency in data collection, selection of end of life thresholds, and treatment of the pavement system as a non-repairable system (there is a specific end of life) when in fact it is a repairable system (includes the application of maintenance and rehabilitation treatments). There currently is no uniformity among agency practices in terms of calculating RSL.

Recommendations

The recommended approach for analyzing the consequences of delayed pavement maintenance uses individual distress metrics rather than a composite index. Given that the wide variability in pavement data between states, the approach is flexible enough so that implementing agencies can select the metrics for the analysis that are best suited for their situation.

Other Asset Performance

Looking beyond pavements and bridges, methods used to report the condition of roadside assets vary widely by asset type and by agency. Approaches include observed condition, age, and customer complaints.[40] A common mechanism for communicating the condition of these types of assets is maintenance level of service (LOS). LOS often is expressed using either letter grade buckets (A through F) where A indicates that the asset is in excellent condition and F indicates the asset is in a failed condition[41] or number grades ranging from 0 (bad level of service) to 100 (excellent level of service). The definition of LOS, data collection protocols, and LOS calculation methodologies vary significantly among state DOTs.

Recommendations

The NCHRP 14-20 research team will develop recommendations for other assets during Phase II of the work (described in section 6.0).

3.4 Infrastructure Modeling Approaches

Two key components of infrastructure modeling include models used to forecast deterioration, and optimal maintenance policies that indicate what work should be performed and when. There are two basic approaches for developing these types of models for pavements and bridges: the Delphi method and the data-driven method:

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[40] Markow, M.J., 2007.

[41] *Business Process Improvement Program: Maintenance Level of Service Budget Manual,* Louisiana Department of Transportation.

The Delphi method is a process of structured expert elicitation.[42] In the context of infrastructure management, the Delphi method can be used to define a deterioration model or a maintenance policy. For example, DOT staff with significant experience applying maintenance actions and observing the impact of those actions on infrastructure conditions can apply the Delphi method to combine their knowledge into a single, commonly agreed-upon, model for predicting future conditions. Similarly, they could apply the Delphi method to select proper maintenance actions based on their knowledge of the long term costs and benefits of potential actions. There are no specific analytical models for applying this method, but often agencies collect and analyze structured data using an asset management systems to aid in the decision-making process.

In the **data driven method**, agencies use historical data to develop statistical relationships between condition and maintenance actions, or between maintenance actions and agency and user costs to forecast future performance and costs. These types of relationship, combined with rigorous cost optimization techniques to select proper maintenance actions that minimize the long term cost of maintaining the infrastructure.

Bridge Management

Modeling Approaches

Bridge management systems often employ the Delphi method to predict future condition, and the data-driven method, typically minimizing long-term costs, to select proper maintenance actions. The long term cost optimization methods employ memoryless Markov Decision Processes (MDP) to model element- or component- (deck, superstructure, and substructure) level deterioration. Modelers create memoryless MDPs deterioration models using the Delphi Method (expert elicitation) or using observational field data tracking the condition of bridge elements or components under different conditions and with different maintenance actions. Memoryless indicates that the past deterioration of a bridge element has no impact on the deterioration of the element into the future; to wit, the model estimates the future condition of an element based only on the current condition of the element. The model tracks how bridge elements or components deteriorate when different maintenance actions are applied, and selects those actions as the ‘optimal’ or proper maintenance actions that minimize the agency and user costs of maintaining a bridge element over the long term. There are several available models that employ this basic modeling approach. Examples include:

- **Pontis.** Pontis, in use by a large portion of state DOTs, is a state-specific tool that optimizes maintenance decisions at the element level and simulates

[42] Linstone, H.A., Turoff, M., *The Delphi Method: Techniques and Applications,* 2002.

bridge-level functional improvements (e.g. full bridge replacement) based on functional standards and user cost triggers.[43] Most agencies customize the system's underlying cost and deterioration models before using it to analyze bridges. In Pontis, condition data are collected and stored at the bridge element level.

- **National Bridge Investment Analysis System** (**NBIAS)**. NBIAS is a bridge management software tool created for and used by FHWA to analyze the needs of the nation's bridges. NBIAS optimizes element-level maintenance decisions but does not include bridge-level simulation.[44] Because NBIAS is meant to analyze national bridge investment needs, it includes national default deterioration models and the data come from the National Bridge Inventory (NBI) file.[45] In NBIAS, component-level (e.g., deck, superstructure, and substructure) data in the NBI file are converted to element-level data prior to analysis using a statistical model.
- **Bridge Needs Analysis Model (BNAM)**. BNAM is a tool created and used by the New York State Department of Transportation. BNAM is capable of modeling optimal maintenance policies on bridge decks, superstructures, and substructures. The deterioration model is specific to New York and uses a unique condition rating system. BNAM is focused on routine maintenance and includes fewer maintenance activities than Pontis and NBIAS.[46]
- **Project Level Analysis Tool (PLAT).** PLAT was developed by the Florida Department of Transportation to assist in the bridge-specific project scoping analysis. While the tool is based on the Pontis approach for modeling optimal preservation policies, the approach has been modified to account for Florida-specific issues and project-level concerns, for example by enabling users to specify project-specific costs and scoping decisions. The tool also provides a display tool that helps the DOT assess timing and scope options.[47]

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[43] Cambridge Systematics, *Pontis Modeling Approach Overview*, presentation prepared for the FHWA, May 2004

[44] Cambridge Systematics, *NBIAS 3.4 Technical Manual,* prepared for the FHWA, April 2010.

[45] DOTs are required to submit National Bridge Inventory (NBI) data to the Federal Highway Administration (FHWA) for all bridges on or over U.S. roads and for culverts longer than 20 feet.

[46] Christian, George A, "Inspection Data for Bridge Asset Management, NY State DOT Approach and Practice", presentation to the Vermont AOT Bridge Maintenance and Preservation Conference, July 2008.

[47] Thompson, Paul D. and John O. Sobanjo**,** *Project Level Analysis Tools User Manual*, prepared for the Florida DOT, March 2004.

- **Multi-Objective Optimization System (MOOS).** MOOS provides network and bridge-level tools. The bridge-level tools are similar to PLAT. There also is a network-level tool for multi-objective optimization. Both tools use a an approach to preservation modeling that is similar in nature to the approach used by Pontis and NBIAS.[48]

Recommendations

The state of the practice is best represented by the modeling approach used by Pontis and NBIAS. There have been several improvements to this approach, including, for example, those made in the MOOS and PLAT model. However, the NCHRP 14-20 research team recommends using an approach based on NBIAS because the tool includes many national defaults needed for the analysis, and because data required to use the NBIAS models are readily available for all states through the NBI files.

However, it is not recommended that NBIAS be used directly. The current structure of the system is the is not designed to project the costs of delayed maintenance as defined for this project. Instead, it is recommended that key components of NBIAS be transformed into a prototype model that can be used with any NBI file to estimate the cost of delayed bridge maintenance. These key components are element deterioration models, an optimal maintenance policy, and the agency and user costs associated with each maintenance action.

Pavement Management

Modeling Approaches

In pavement management systems, there is little consistency in the modeling approaches used to forecast condition and select proper maintenance. Many state DOTs have developed state of the art models that can that forecast the condition of pavements. These models typically represent historical performance patterns, predict deterioration rates and forecast future trends for different maintenance actions. Practitioners typically model pavement deterioration over time using various mathematical forms ranging from linear regression to Markov probabilistic models. In addition to pavement age, some models incorporate other factors such as climatic region, traffic, subgrade and other design features as predictor variables for further stratification. Besides regression-based models, there is a growing interest in using mechanistic-empirical models, such as the

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[48] Patidar, Vandana et.al., *Multi-Objective Optimization for Bridge Management* NCHRP Report 590, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, 2007.

Mechanistic-Empirical Pavement Design Guide (MEPDG) and HDM-IV, for performance modeling.[49]

Many agencies employ economic cost analysis in concert with deterioration models to develop proper maintenance actions based on the expected benefit that a maintenance action provides and its required costs.[50] This methodology typically is different than the minimum long-term cost method employed by bridge management systems, though it too is based on the analysis of performance and cost data. The economic efficiencies of various scenarios can be compared using cost-benefit analysis by normalizing the treatment effectiveness (benefits) by the present value of costs.[51] Life cycle cost concepts are heavily used in pavement analysis. For example, the FHWA has a Technical Bulletin that provides detailed guidance for incorporating Life-Cycle Cost Analysis (LCCA) into pavement design.[52] Examples of common economic metrics include Equivalent Annual Cost (EAC), Net-present value (NPV), and Benefit-cost ratio (BCR).

Despite the prevalence of long term cost optimization models for pavements, there is no consensus among agencies on the details of this approach. One of the byproducts of the wide variety of pavement condition data collected by state DOTs (discussed above) is the variety of pavement management systems and tools used by these agencies.

Recommendations

For the purposes of calculating the consequence of delayed pavement maintenance, the NCHRP 14-20 research team recommends an approach that can be tailored to an agency's specific pavement management practices. Given the wide range of pavement management practices and pavement data protocols used throughout the U.S., this flexibility is vital for agencies to adopted the NCHRP 14-20 methodology. The recommended approach, which is described in detail below, relies on custom deterioration curves that can be developed with historic condition data, and addresses the selection of work activities through the Delphi method.

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[49] Li, J, S.T. Muench, et.al, *Applications of HDM-4 in the WSDOT Highway System,* Report No. WA-RD 588.1, Washington State Transportation Commission, 2004.

[50] Peshkin, D.G., et.al., Optimal Timing of Pavement Preventive Maintenance Treatment Applications, NCHRP Report 523, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, 2004.

[51] Wei, C. and S. Tighe, "Development of Preventive Maintenance Decision Trees Based on Cost-Effectiveness Analysis: An Ontario Case Study," Transportation Research Record No.1866, Transportation Research Board, Washington, DC, 2004.

[52] FHWA, *Life-Cycle Cost Analysis in Pavement Design, Pavement Division Interim Technical Bullitin, FHWA* Publication No. FHWA-SA-98-079, September 1998.

Other Asset Management

Modeling Approaches

Many transportation agencies use maintenance management systems (MMS) to plan, schedule, and track maintenance activities. Agencies typically do not apply the same degree of analytic rigor to the management of "other assets", although management systems have been developed for some specific asset types. Few MMS integrate economic features typically found in pavement and bridge management systems.

Also, there is a general lack of understanding on how other assets deteriorate with time. Given the lack of deterioration models, many agencies use some combination of preventive maintenance policies, age-based models, reactive strategies, and worst-first strategies to maintain their systems. These approaches rely heavily on historic president, extensive experience, local knowledge, and engineering judgment. Many agencies also use maintenance levels of services (LOS) to inform the maintenance management process. LOS provide a means for translating observed conditions into a simple scale that is easily communicated. Many agencies track LOS trends over time, and a few have worked to predict them based on different funding scenarios. Despite the prevalence of LOS approaches, there is no standard for how DOTs collect or assess data on other assets, and there is significant variety between agencies on how they maintain them.

Recommendations

The NCHRP 14-20 research team will develop recommendations for other assets during Phase II of the work (described in section 6.0).

4.0 Analyzing the Consequence of Delayed Bridge Maintenance

Bridge management systems are well developed, widely used in practice, and help agencies ask "what-if" questions about how funding and policy decisions impact the health of their bridge network and the balance of their budget. While the most widely used systems are not designed to directly analyze the consequences of delayed maintenance, it is possible to leverage components of these systems and develop a tool that can. This section describes a modeling approach and prototype tool that take advantage of years of effort by the FHWA to develop the National Bridge Inventory Analysis System (NBIAS). The resulting prototype tool is designed to enable agencies to conduct sketch level analyze of the cost of delayed bridge maintenance using only the National Bridge Inventory (NBI) data set, which is available for every state in the U.S. This section also presents the results of a pilot application of the tool, using NBI data from four states.

4.1 Key Assumptions

The NCHRP 14-20 prototype bridge tool relies heavily on the modeling approach implemented within NBIAS. Following is a summary of key assumptions built into the NBIAS approach that are manifested into the prototype tool. For a more complete description of the technical approach used by NBIAS, refer to the *NBIAS Technical Manual*. [53]

Maintenance, rehabilitation and repair (MR&R) policy. NBIAS generates an optimal MR&R policy that recommends a treatment for each element in each condition state based on the following:

- *Condition information.* Bridge condition is captured at the bridge component level (e.g., deck, superstructure, substructure, and culvert) based on the results of a visual inspections. These data are stored in the National Bridge Inventory (NBI) file. Conditions are based on a scale of one (excellent condition) to five (very poor condition) with an additional failed condition. NBIAS translates component level data into bridge element level data (e.g., deck, bearing, girders, etc.) using the NBIAS Synthesis, Quantity, and Condition (SQC) model. The remainder of the MR&R analysis is conducted using this synthesized element-level data.

[53] Cambridge Systematics, *NBIAS 3.4 Technical Manual,* prepared for the FHWA, April 2010.

- *Transition probability matrices.* NBIAS models bridge element deterioration using memoryless Markov decision processes (MDP). The hallmark of an MDP is that it is a simple probability matrix that identifies, for each element type, and each current condition state, under each maintenance action, and each climate zone. The probability that the element will remain in its current condition state or that it will transition from its current condition state into an improved condition state (e.g. under the replacement maintenance actions) or a deteriorated condition state (e.g. under the do nothing maintenance action) or that it will fail. Table 4.1 shows an example probability matrix for bare concrete deck.

Table 4.1 Example Probability Matrix – Bare Concrete Deck, Wet Freeze Environment

Initial State	Action	Probability that Element will Move to… State 1	State 2	State 3	State 4	State 5	Probability of Failure
1	do nothing	87%	13%				
	action 1	97%	3%				
2	do nothing		93%	7%			
	action 1	41%	55%	4%			
	action 2	64%	34%	2%			
3	do nothing			84%	16%		
	action 1	30%	10%	55%	4%		
	action 2	71%	12%	17%			
4	do nothing				84%	16%	
	action 1	25%	5%	8%	53%	9%	
	action 2	75%	8%	1%	17%		
5	do nothing					79%	21%
	action 1	42%	7%	2%	1%	49%	
	action 2	100%					

Source: NBIAS, version 3.4

- *Agency costs.* NBIAS includes unit cost estimates for a variety of work activities. MR&R unit costs vary by element and condition state. For example, the cost of repairing spalls and delimitations of a bare concrete deck in condition state 2 is higher than the same work activity in condition state 3. There is also an agency cost associated with an element failing. The agency cost of failure represents a premium over the most expensive action in the worst condition state.

- *User costs.* NBIAS estimates users costs associated with traveling over a bridge. These user costs reflect decreased travel speeds and increased vehicle operating costs associated with deteriorating deck conditions.

The MR&R policy is driven by economic considerations. The NBIAS MR&R policy is designed to minimize life cycle cost rather than to maintain or achieve a specified level of service. One practical implication of this approach is that if a bridge network is currently in excellent condition, NBIAS (and the NCHRP 14-20 prototype tool) may show that its condition decreases over time regardless of budget. In essence, NBIAS will not select work that does not make sense economically. It may not model work until conditions deteriorate to a point in which work is triggered by the MR&R policy.

The MR&R policy works at the bridge element level. NBIAS creates an MR&R policy by considering the optimal work for individual bridge elements. It does not evaluate MR&R work at the bridge level. Bridge replacements are driven by functional needs rather than the MR&R model. There are two key implications of using the NBIAS MR&R policy in the NCHRP 14-20 prototype tool:

- The tool is unable to model how delayed maintenance might impact the need for bridge replacement. Since the MR&R policy does not assess bridge replacement costs, the costs of delayed maintenance calculated by the prototype tool represents the lower bound. If bridge replacement were included in the model, the overall costs of delayed maintenance on very poor bridges would likely increase. For example, if some critical mass of bridge elements on a bridge required extensive work, an agency may opt to replace the entire bridge instead of working on the individual elements.
- The tool assumes that all MR&R work falls under the category of "maintenance". Transportation agencies distinguish the difference between maintenance work and non-maintenance in different ways. For example, select work on hand full of elements on a bridge may be considered to be "maintenance." More extensive work, however, may be packaged into a bridge rehabilitation project that may be considered by an agency to be a capital project rather than a maintenance project. However, in keeping with the definition of maintenance recommended in Section 3.0, the prototype tool considers all MR&R activities to be maintenance activities.

User cost models account for a subset of potential costs. NBIAS estimates user costs by assessing the impact that bridge deck condition has on travel speed and vehicle operating costs. It also considers detour length, when a bridge is taken out of service. However, as described above, since bridge replacements are driven by functional needs rather than the MR&R policy, the NCHRP 14-20 prototype tool does not capture the potential for increased user costs due to bridge closures associated with bridge replacement projects.

The MR&R policy assumes a discount rate of 7 percent. NBIAS includes a national default MR&R policy that seeks to minimize the long term costs of

bridge maintenance. The default policy (which has been incorporated in the NCHRP 14-20 prototype bridge tool) reflects a discount rate of 7 percent.

Use of national default values. NBIAS includes national default values for agency costs, user costs, and deterioration probabilities. The defaults are based on analysis conducted by the FHWA and have been validated for accuracy for national level FHWA planning applications. These defaults have been incorporated into the NCHRP 14-20 prototype bridge tool, and are the basis for the pilot results described below. The use of national defaults helps to strike a balance between providing the benefits of a sketch planning tool while decreasing the amount of work required by an agency before applying it. Advanced users of the prototype tool can update these defaults.

4.2 ANALYSIS APPROACH

This section describes the approach used to evaluate the consequence of delayed maintenance. The approach is consistent with the framework described in section 2.0.

Define the cost of delayed maintenance. The approach to quantify the costs of delayed maintenance compares agency and user costs accrued over a fifteen year analysis period in one scenario (the baseline scenario in which maintenance is performed) to another (the delayed maintenance scenarios). In the baseline scenario, an agency properly maintains the system, where 'proper' maintenance is defined as following the NBIAS MR&R policy, and therefore seeking to minimize long term costs. Each delayed maintenance scenario is defined by the extent of delayed maintenance, the delayed maintenance package, and the duration of delayed maintenance.

- *Extent of delayed maintenance.* The agency maintains only the portion of the system that funding allows and delays maintenance on the remainder of the system until funding is restored. The agency selects a mix of bridges in good and poor condition in an attempt to strike a balance between minimizing long term cost as much as possible and maintaining systems conditions as much as possible. For the analysis, the extent varies from 0 to 100 percent of the system.
- *Delayed maintenance package.* The agency performs no maintenance but replaces elements when they fail. After the deferral period, the agency performs the recommended actions on the entire system.
- *Duration of delayed maintenance.* The agency delays maintenance for a period of 1 to 10 years. *A*t the end of the duration, the agency immediately performs the recommended maintenance to the full extent of the system and continues to do so until the end of the fifteen year analysis period.

This approach enables agencies to define and analyze several delayed maintenance scenarios to show how the duration of maintenance delay and the extent of maintenance delay impact the consequences of delayed maintenance.

Calculate annual costs and network condition. The prototype tool enables users to calculate the consequences of the delayed maintenance separately for 101 scenarios: the baseline scenario and 100 delayed maintenance scenarios. The delayed maintenance scenarios are defined by a combination of extent and duration, as illustrated in Table 4.2.

Table 4.2 Delayed Maintenance Scenarios

Percent of network maintained (extent)	Duration of Delay in Years				
	1	2	3	…	10
0	Scenario 1	Scenario 2	Scenario 3	…	…
10	Scenario 11	Scenario 12	…	…	…
20	Scenario 21	…	…	…	…
…	…	…	…	…	…
90	…	…	…	…	Scenario 100

For illustrative purpose, following is a description of how the tool calculates the cost of delayed maintenance for Scenario 12. As indicated in Table 4.2, in Scenario 12 only 10 percent of the network is maintained (maintenance is delayed on 90 percent of the network) for two years. After year 2, the recommended MR&R actions are applied in each of the remaining 15 years in the analysis period. The analysis approach illustrated below is the same for the other scenarios.

1. Analyze the Baseline Scenario:
    a. In year 1, the tool applies the maintenance package, in which NBIAS default MR&R policy is followed for the entire network. The tool selects an activity for each element based on its condition.
    b. The tool projects the resulting condition of each element in year 2 based on the condition in year 1 and the work performed, using the transition matrix, which is illustrated in Table 4.1.
    c. In year 2, the tool selects an activity based on the updated condition state developed in step b.
    d. The tool repeats steps b. and c. for each year, through year 15.
2. Analyze Delayed Maintenance Scenario 12:
    a. The tool defines two subnetworks. The first represents the 10 percent that will be maintained. The second represents the 90 percent on which maintenance is delayed.

b. The tool treats the 10 percent subnetwork the same as described above for the Baseline Scenario.

c. For the 90 percent subnetwork, in year 1, the tool applies the delayed maintenance package, in which no work is performed unless an element transitions into the failure state. If an element is in the failure state, a the failure agency cost is incurred.

d. The tool projects the condition of elements in year 2 based on the condition in year 1 and the work performed, using the transition matrix. Once work is conducted on a failed element, it is moved to condition state 1.

e. The tool applies the delayed maintenance package for year 2 (the final year of the duration).

f. The tool projects the condition of elements in year 3 based on the condition in year 2 and the work performed.

g. Starting in year 3, the tool follows the default MR&R policy for each year through year 15, following the same approached used for the Baseline Scenario.

Calculate the consequences of delayed maintenance. The tool reports the consequences of delayed maintenance in terms of:

- The difference in agency and user costs between the Baseline Scenario and each Delayed Maintenance Scenario over the 15 year analysis time period; and
- The change in network condition between the Baseline scenario and each Delayed Maintenance Scenario.

For each scenario, the tool discounts agency and users costs into first year dollars and sums them. The costs of each Delayed Maintenance Scenario are calculated as the cost of that scenario minus the cost of the Baseline Scenario. The tool also reports the network health index in the final year of the duration and at the end of the 15 year analysis period.

4.3 PROTOTYPE TOOL

This section describes the use of the prototype bridge tool developed as part of this research effort. It has been built as a spreadsheet tool that enables users to quickly and easily performing sketch planning level analysis of the consequences of delayed bridge maintenance. The tool automates the analysis approach described in the previous section.

To estimate a state-specific cost of delayed maintenance a user must do the following:

Select a State. NBIAS provides a set of national unit costs and a cost coefficient for each state that can be used to adjust the default unit costs. It also provides an MR&R policy for several climate zones. When a user selects a state in the prototype tool, the it automatically pulls the appropriate cost coefficient and climate zone, and incorporates the appropriate values into the analysis.

Specify element level inventory condition data. Users are required to input element-level inventory and condition information into the tool. For example, Table 4.3 presents an excerpt of concrete deck elements for state owned bridges in Massachusetts, developed during the pilot application (described below). The table is an expert of the input data required by the prototype bridge tool. This input could be drawn from an agency's Pontis database or, as in the case of the pilot applications, estimated by using the NBIAS Synthesis, Quantity and Condition (SQC) model. The SQC model, which has not be incorporated into the prototype tool, was developed by FHWA to synthesis element level inventory and condition data based on data in the National Bridge Inventory (NBI) file.

Table 4.3 Example of Concrete Deck Elements for a State

Element Name	Total (each)	Condition State 1	Condition State 2	Condition State 3	Condition State 4	Condition State 5
Concrete Deck - Bare	324,454	172,931	151,046	476	0	0
Concrete Deck - Unprotected w/ AC Overlay	91,381	34,607	49,050	7,725	0	0
Concrete Deck - Protected w/ AC Overlay	1,595,503	890,824	696,119	8,528	32	0
Concrete Deck - Protected w/ Thin Overlay	21,575	3,826	16,913	836	0	0
Concrete Deck - Protected w/ Rigid Overlay	81,686	44,895	36,791	0	0	0
Concrete Deck - Protected w/ Coated Bars	982,530	679,384	300,792	2,355	0	0

Source: Cambridge Systematics, Inc. based on estimates developed by NBIAS using the 2010 National Bridge Inventory File for one of the pilot states (discussed below).

Once a users provides the input described above, the tool analyzes all 101 maintenance scenarios. Prior to the analysis, advanced users can customize the tool. Because the tool has been developed as spreadsheet, users are able to review the underlying assumptions and make the following types of changes:

Selecting a certain network of bridges for analysis. If a users wants to estimate the cost of delayed maintenance on a subset of critical bridges (e.g. interstate bridges), they could filter the bridge data prior to entering it into the tool.

Customizing the MR&R policy. The tool uses the default NBIAS MR&R policy which indicates the recommended maintenance actions for each element in each condition state in each climate zone. However, this policy can be updated in the tool if a user wishes to specify a custom work policy. Users could specify an MR&R policy using the same potential work actions, or remove certain actions from the analysis that may not be considered to be "maintenance."

Customizing agency and user costs. The tool contains NBIAS default user and agency costs. These costs can be updated to reflect agency-specific costs.

4.4 PILOT APPLICATION

The research team used the prototype tool to analyze bridge data from four states, representing different geographic regions, climate zones, traffic levels, and bridge ages. The section describes the approach and findings from this pilot analysis.

Selection of Pilot States

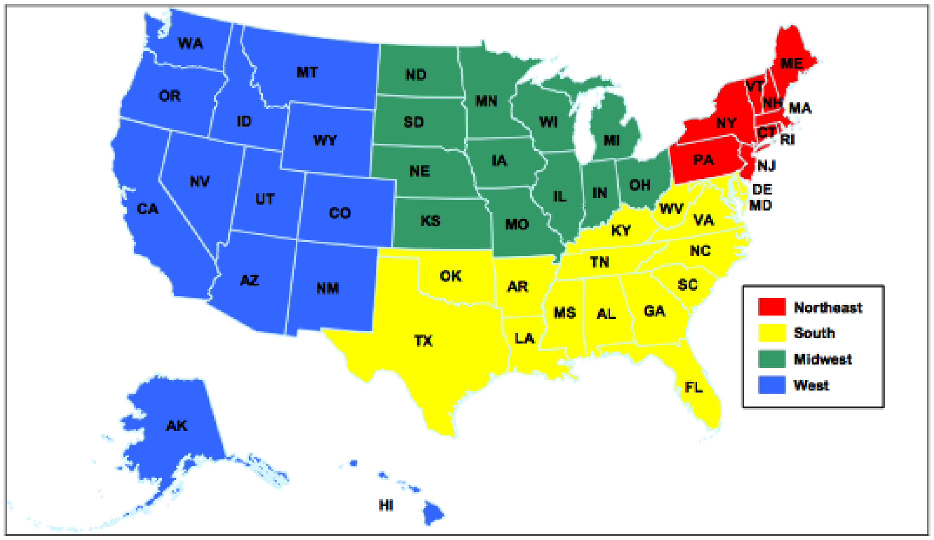
The approach used to select these states draws heavily from a recent comparative study conducted as part of NCHRP 20-24(37)E, Measuring Performance Among State DOTs, Sharing Best Practices— Preservation: Comparative Analysis of Bridge Conditions.[54] As part of NCHRP 20-24(37)E, peer groups of states were identified, in order to provide a basis for comparing data among states with similar characteristics impacting bridge performance.

The following criteria were considered when selecting the pilot states:

Geographic region. Figure 4.1 illustrates the geographic region peer groups used in NCHRP 20-24(37)E. The 20-24(37)E research team found that differences in bridge conditions across the U.S. were the most pronounced when compared across these geographic regions. Each state included in the pilot is located in a different geographic region.

[54] Spy Pond Partners, LLC and Arora and Associates, *Measuring Performance Among State DOTs, Sharing Best Practices— Preservation: Comparative Analysis of Bridge Conditions*, developed through NCHRP 20-24(37) E, August 2010.

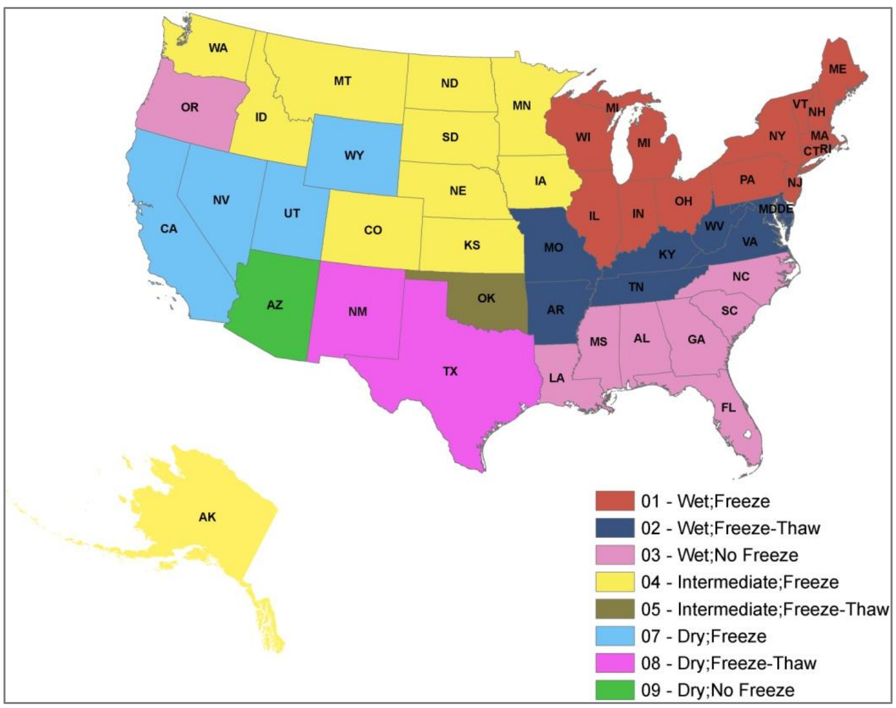
Figure 4.1 Geographic Regions



Source: NCHRP 20-24(37)E Final Report.

Climate zone. Figure 5.2 illustrates the climate zones used by NBIAS. Each pilot state is from a different climate zone.

Figure 4.2 Climate Zones



Source: CS based on NBIAS parameters

Traffic level. NCHRP 20-24(37)G defined the traffic categories, which are based on the following thresholds for average daily traffic (ADT) per lane:

- Low < 5,000
- Medium 5,000 to 9,000
- High > 9,000

Bridge age. NCHRP 20-24(37)G also defined age categories, which are based on the following thresholds for percent of bridge deck area on bridges greater than 40 years old:

- Low < 20
- Medium 20 to 30
- High > 30

Based on analysis of these criteria, the research team selected four pilot states. Table 4.4 illustrates the distribution of these states in terms of the criteria defined above. Since this is a research effort involving the piloting of a new analysis approach, the results of the analysis are presented "blindly", so that results are not associated with specific states.

Table 4.4 Proposed Validation States and Peer Group Criteria

State	Geographic Region	Climate Zone	Traffic Volumes	Bridge Age
State 1	South	3	Medium	Low
State 2	Northeast	1	High	High
State 3	Midwest	4	Low	Medium
State 4	West	7	High	Low

Results of Pilot Analysis

The research team developed results for the four pilot states. In each case, the respective 2010 NBI file was obtained, and non-state owned bridges were filtered out. NBIAS was then used to translate the remaining NBI data into a synthesized network of elements, as illustrated in Table 4.3. Following is summary of the findings from the pilot analysis:

- Delaying bridge maintenance for up to 10 years can result in a decrease in agency costs over a 15 year analysis period.
- Delaying bridge maintenance increases user costs. The increase in user costs is directly proportional to the length of the delay duration.

- The increase in user costs outweighs the decrease in agency costs. Therefore, there is a net cost associated with delaying bridge maintenance.
- There can be a substantial one-time cost to perform the recommended maintenance activities in the year following end of the delay duration.
- Delaying maintenance can cause the network health to decline rapidly. However, applying the recommended MR&R policy after the delay duration for the remainder of the 15 year analysis period can eventually improve the network health to where it would have been under the maintenance scenario.

The five findings listed above are consistent among all four states. Each finding is discussed in more detail below.

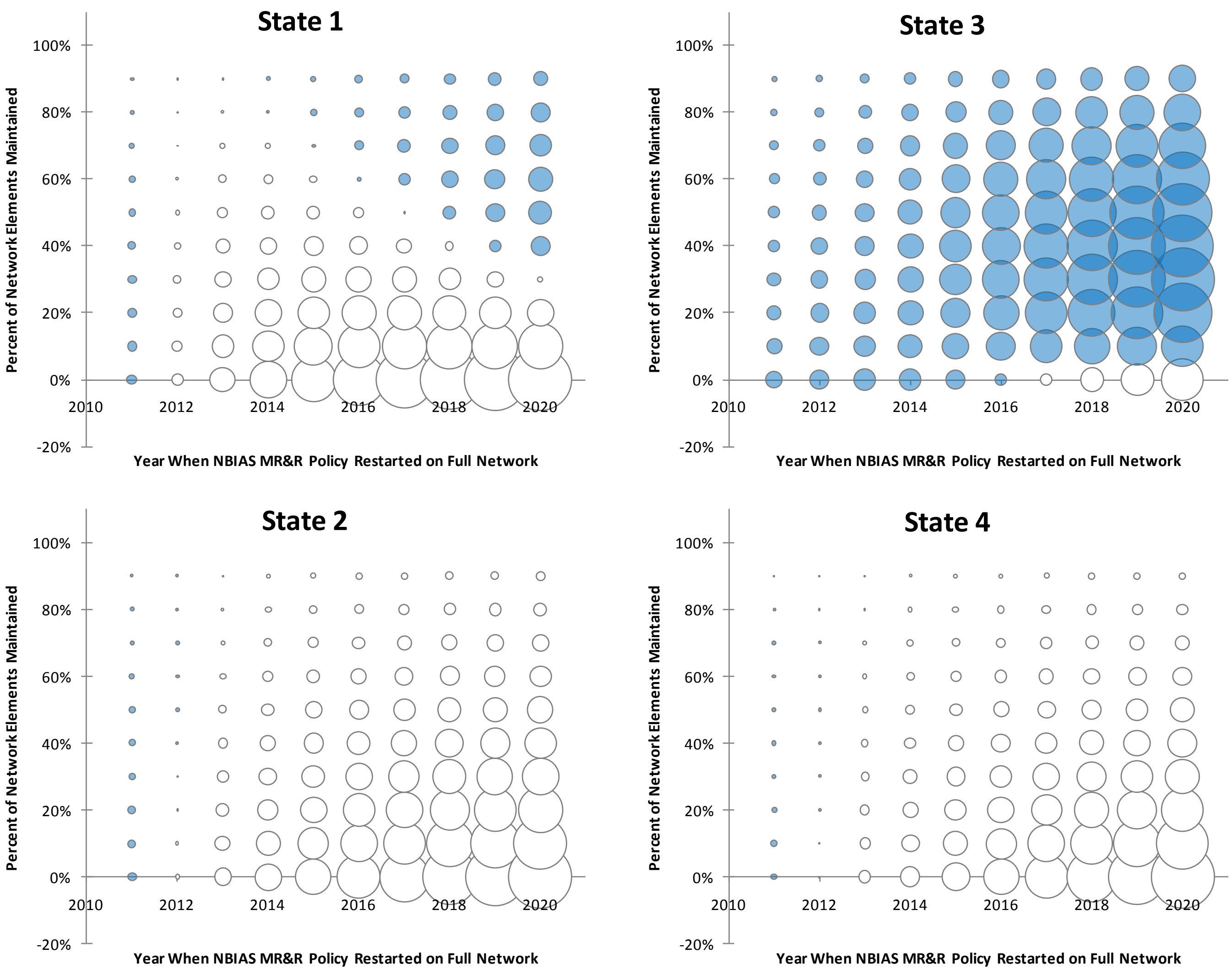
Delayed Maintenance can Decrease Agency Costs

Over the 15 year analysis period and in each pilot state, the results indicate that agency costs would decrease if maintenance were delayed on 100 percent of the network (maintaining 0 percent of the network) for 10 years. The agency savings in other scenarios depends on the original condition of the elements, the relative cost of maintenance actions, and the climate zone.

Figure 4.3 presents agency costs (solid blue dots) and savings (empty white dots) over each of the delayed maintenance scenarios for each of the pilot states. In the graph, the dots change in size proportional to the agency cost or savings. A big blue dot indicates a relatively high net agency cost (i.e., delaying maintenance costs money). A big white dot indicates a relatively high agency savings (i.e., delaying maintenance saves money).

Each row in the chart represents the percent of bridge elements maintained in the network, and each column represents the year when full maintenance is restored after delay. For example, the cost of maintaining 80 percent of the elements in the network but delaying maintenance on the remaining 20 percent until 2015 is found by finding 80 percent on the y-axis and following it until reaching 2015 on the x-axis. In general, agency costs decrease and savings increase as less of the network is maintained (*extent)* and as the *duration* of the delay increases (reading the graph from top-left to the bottom-right).

Figure 4.3 Change in Agency Costs for Various Delayed Maintenance Scenarios



Notes

Solid dots represent a net cost associated with delayed maintenance

Empty dots represent a net savings associated delaying maintenance

The size of the dots is proportional to the amount of costs and savings.

Figure 4.3 shows two types of results. In States 2 and 4, agency costs decrease in almost every delayed maintenance scenario. In States 1 and 3, the results fluctuate between a net increase and a net decrease. The research team conducted a sensitivity analysis to try to locate the cause of these differences. Recall that in terms of the pilot analysis, the three main variables between the four pilot states are 1) the size and initial condition of the bridge network, 2) the relative cost of maintenance activities (as reflected in the state cost adjustment factors provided in NBIAS), and 3) the climate zone. The sensitivity analysis showed that the driving factor in the results is climate zone. The MR&R policy varies by climate zone. Harsher climates lead to increased levels of deterioration, and therefore require a more aggressive maintenance strategy. The pilot analysis showed the largest decreases in agency costs in states with relatively harsh climates.

The findings that delaying bridge maintenance up to 10 years can result in a net decrease in agency costs, and that these decreases are the highest in harsh climate zones can be counterintuitive. Conventional wisdom says that delaying maintenance will require more dramatic, costly activities in the future, therefore increasing overall costs. However, the research team believes that results show a net savings in agency costs for the following reasons:

- The pilot bridge networks were in relatively good starting condition;
- Bridges, especially ones in good condition, can deteriorate relatively slowly, for example as compared to pavements;
- The analysis only covered a delay duration of up to 10 years;

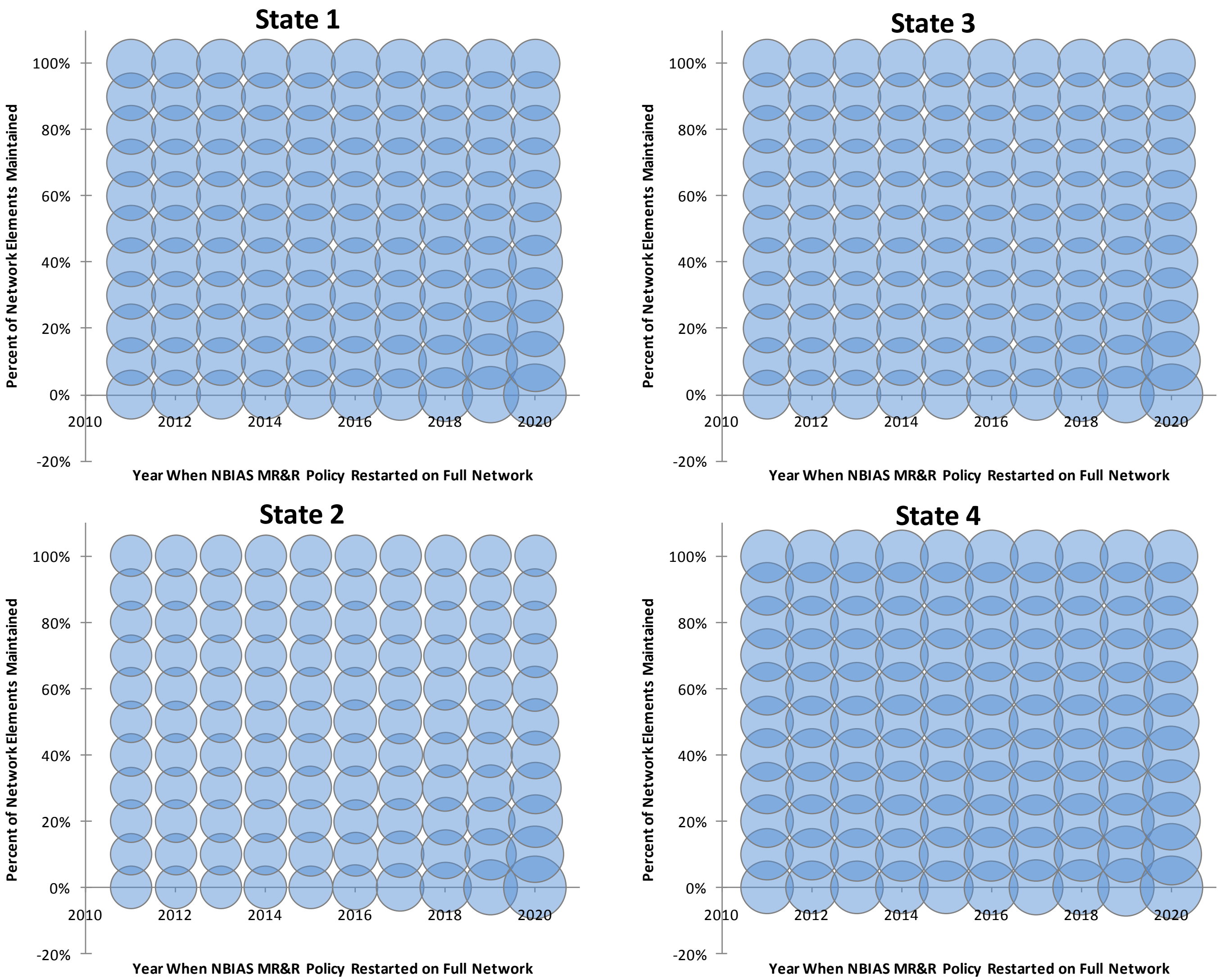
A review of the NBIAS MR&R policy suggests that the theory that a lack of maintenance will eventually lead to increased deterioration and an increase in cost is true. However, the theory is only true when a bridge element approaches a condition state that triggers a major increase in the cost of the recommended activity. This can occur when a bridge element has a poor initial condition, or when maintenance is delayed for extended periods. These conditions did not widely exist in the pilot analysis. In each case, the networks were in relatively good condition, and maintenance was only delayed for up to 10 years.

Another major factor in the analysis is the time value of money. For example, delaying work for ten years, and then performing it in year 11 can lead to an overall decrease in the net present value of work due to the time value of money. This helps explain why the cost savings found in the pilot are the most pronounced in the harsher climate zones; climate zones in which more aggressive/expensive maintenance strategies are recommended. Delaying this work can decrease its net present value.

Delayed Maintenance can Increases Users Costs

Over the 15 year analysis period, in each of the 100 delayed maintenance scenarios, and in each of the states, the users are predicted to experience significant cost increases. When maintenance is delayed, bridge decks deteriorate, and users experience increased vehicle maintenance cost and additional travel time. Figure 4.4 presents the user cost results. In the graphs, the blue dots increase in size proportional to the user costs. The blue dots represent the net cost to users of delaying maintenance. In each state, user costs are projected to increase as the percent of network maintained (*extent)* decreases and the *duration* of delay increases (reading the graph from the top-left to the bottom-right).

Figure 4.4 Change in User Costs for Various Delayed Maintenance Scenarios



<u>Notes</u>

Solid dots represent a net cost associated with delayed maintenance

Empty dots represent a net savings associated delaying maintenance

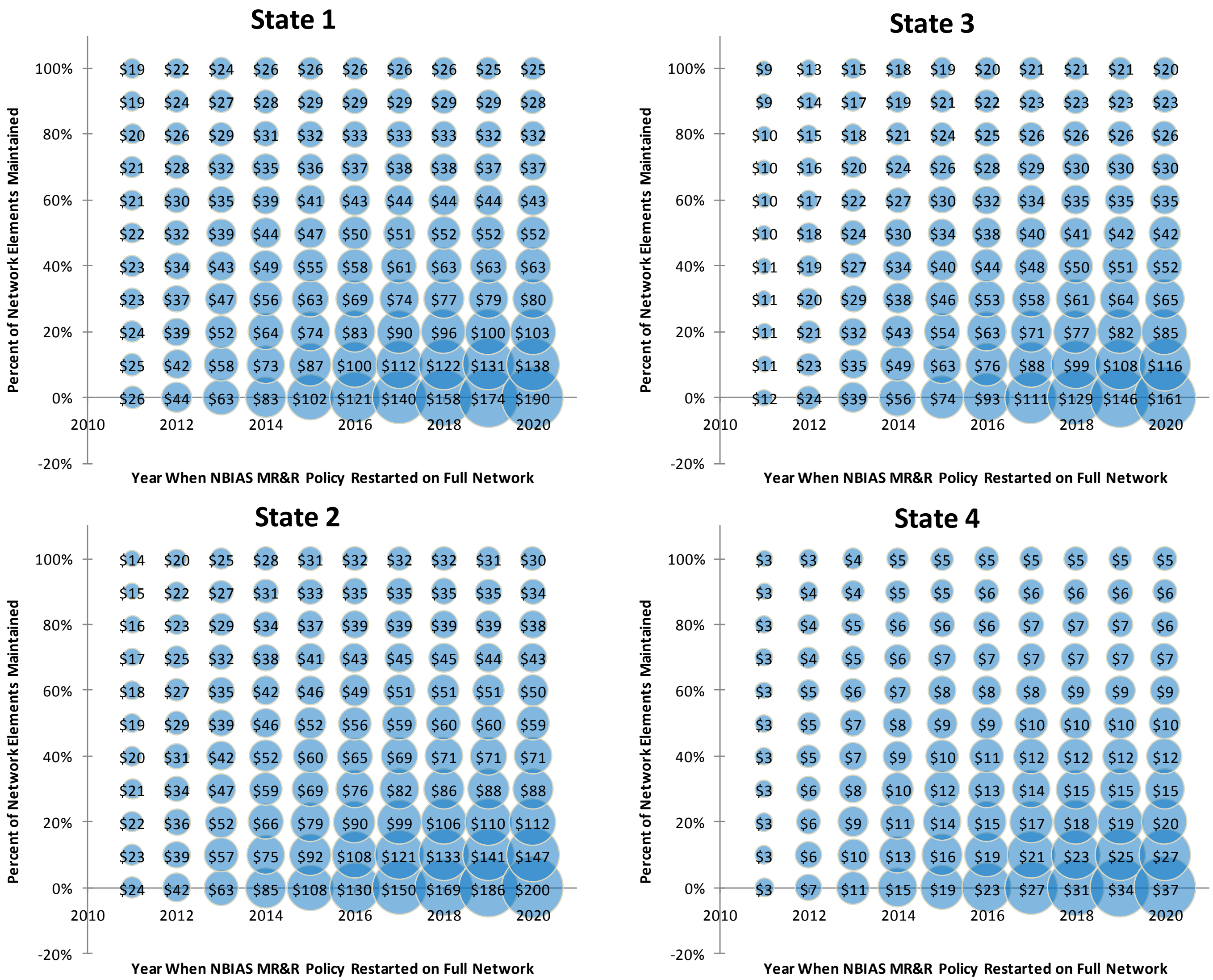
The size of the dots is proportional to the amount of costs and savings.

User Costs Increases Outweigh Agency Savings

The total cost of delayed maintenance in each of the 100 delayed maintenance scenarios and in each of the states is positive because the users incur more costs than agencies experience savings. Figure 4.5 presents the costs of delayed maintenance. Each dot is sized proportionally to the total costs incurred by the agency and user over the 15 year analysis time period.

Table 4.5 provides additional numeric details of selected scenario comparisons to complement figure 4.5.

Figure 4.5 Change in Total Costs (millions) of Various Delayed Maintenance Scenarios



<u>Notes</u>

Solid dots represent a net cost associated with delayed maintenance

Empty dots represent a net savings associated delaying maintenance

The size of the dots is proportional to the amount of costs and savings.

Table 4.5 Comparing the Total Cost of Delayed Maintenance for Select Scenarios

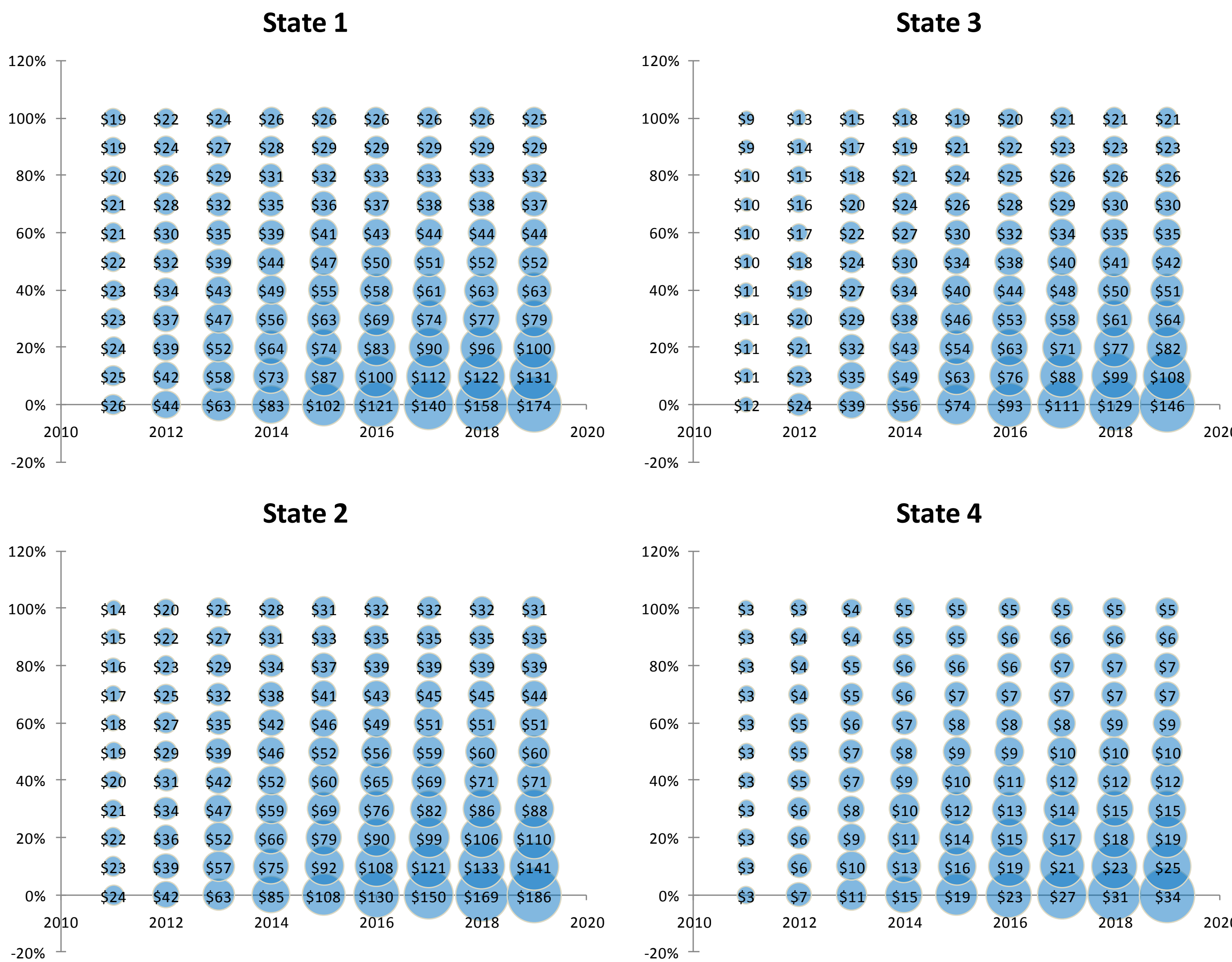
		Baseline Scenario	Selected Delayed Maintenance Scenarios (X% of network is maintained)					
		100%	80%		50%		20%	
Duration of Delay	Cost Category	Cost	Cost	Cost of Delay	Cost	Cost of Delay	Cost	Cost of Delay
State 1								
	Agency	$343,577,215	$343,614,364	$37,150	$342,556,278	($1,020,936)	$339,362,715	($4,214,499)
5 years	User	$54,719,215	$212,445,075	$157,725,860	$213,980,945	$159,261,729	$215,892,410	$161,173,194
	Total	$398,296,430	$556,059,440	$157,763,009	$556,537,223	$158,240,793	$555,255,125	$156,958,695
	Agency	$343,577,215	$345,293,209	$1,715,994	$345,635,695	$2,058,480	$337,709,790	($5,867,425)
10 years	User	$54,719,215	$232,717,279	$177,998,064	$224,778,648	$170,059,433	$245,759,424	$191,040,209
	Total	$398,296,430	$578,010,488	$179,714,057	$570,414,343	$172,117,913	$583,469,214	$185,172,784
Sate 2								
	Agency	$394,767,353	$393,867,758	($899,595)	$390,761,214	($4,006,140)	$383,787,884	($10,979,469)
5 years	User	$135,212,310	$229,884,333	$94,672,024	$231,959,644	$96,747,334	$235,475,488	$100,263,178
	Total	$529,979,663	$623,752,092	$93,772,429	$622,720,857	$92,741,194	$619,263,372	$89,283,709
	Agency	$394,767,353	$392,368,440	($2,398,913)	$384,492,054	($10,275,299)	$363,981,591	($30,785,762)
10 years	User	$135,212,310	$236,197,594	$100,985,285	$253,764,719	$118,552,409	$292,247,029	$157,034,719
	Total	$529,979,663	$628,566,034	$98,586,372	$638,256,773	$108,277,110	$656,228,620	$126,248,957

		Baseline Scenario	Selected Delayed Maintenance Scenarios (X% of network is maintained)					
		100%	80%		50%		20%	
Duration of Delay	**Cost Category**	**Cost**	**Cost**	**Cost of Delay**	**Cost**	**Cost of Delay**	**Cost**	**Cost of Delay**
State 3								
5 years	Agency	$255,308,803	$255,867,123	$558,320	$256,504,739	$1,195,936	$256,485,513	$1,176,711
	User	$71,574,966	$171,882,228	$100,307,262	$173,052,765	$101,477,799	$174,875,631	$103,300,665
	Total	$326,883,768	$427,749,351	$100,865,583	$429,557,504	$102,673,735	$431,361,144	$104,477,376
10 years	Agency	$255,308,803	$257,165,087	$1,856,284	$259,874,367	$4,565,565	$259,819,001	$4,510,198
	User	$71,574,966	$176,144,881	$104,569,916	$187,320,351	$115,745,385	$210,518,081	$138,943,115
	Total	$326,883,768	$433,309,969	$106,426,200	$447,194,718	$120,310,950	$470,337,082	$143,453,314
State 4								
5 years	Agency	$66,372,382	$66,301,394	($70,988)	$66,043,612	($328,770)	$65,441,645	($930,736)
	User	$21,586,304	$55,352,092	$33,765,788	$55,582,716	$33,996,412	$55,898,520	$34,312,216
	Total	$87,958,686	$121,653,486	$33,694,800	$121,626,327	$33,667,642	$121,340,165	$33,381,480
10 years	Agency	$66,372,382	$66,111,953	($260,429)	$65,206,220	($1,166,162)	$62,518,074	($3,854,308)
	User	$21,586,304	$56,594,334	$35,008,030	$59,267,181	$37,680,877	$63,741,188	$42,154,884
	Total	$87,958,686	$122,706,287	$34,747,602	$124,473,401	$36,514,715	$126,259,262	$38,300,576

Backlog can Grow Significantly

In each of the 100 delayed maintenance scenarios and each of the pilot states, after the delay period the bridge networks have experienced more deterioration relative to the maintenance scenario. Applying the recommended MR&R policy in the following year leads to a relatively large increase in work activity. This work can represent a significant backlog associated with delaying maintenance. The availability of this influx in funds needed to addressing this backlog should be a factor when considering whether or not to delay maintenance. Figure 4.6 illustrates the one-time agency costs for each of the 100 delayed maintenance scenarios compared to the maintenance scenario. In each case, agency costs increase as the duration and extent of delayed maintenance increase.

Figure 4.6 Agency Costs (millions) in First Year After Delay



<u>Notes</u>

Solid dots represent a net cost associated with delayed maintenance

Empty dots represent a net savings associated delaying maintenance

The size of the dots is proportional to the amount of costs and savings.

Delaying Maintenance can Cause Conditions to Decline Rapidly

In each of the four pilot sates, the network health index declines annually under the maintenance scenario and delayed maintenance scenarios. (As described in Chapter 4.3, the network condition declines over time in the maintenance scenario because the NBIAS MR&R policy is based on least life cycle costs, rather than achieving or maintaining a target condition level.) However, the network health index declines more rapidly in the delayed maintenance scenarios than in the maintenance scenario. These increased rates in deterioration are an intuitive result of delaying maintenance.

Once full maintenance is resumed, after the duration of delayed maintenance has come to an end, the approach estimates a significant one-time sum of money spent on the accumulating backlog. This work results in the network health improving over the subsequent years. The health of the network tends to converge at the end of the 15 year analysis time period. Figure 4.7 illustrates how the health index varies over time in the maintenance scenario and selected delayed maintenance scenarios for State 1. Similar results were found of the other pilot states. Note the distinctive "V" at the low point of the delayed maintenance health index curve. The inflection point indicates the point at which maintenance is no longer delayed. Before the point, health declines faster than in the maintenance scenario. After the inflection point there is a significant increase in network health due to the accumulated backlog being addressed. In all of the selected delayed maintenance scenarios, after the 15 year analysis period, the health index approaches the health index of the maintenance scenario after the same time period.

Table 4.6 summarizes the network health index findings for all four pilot states under selected scenarios. Note that in State 1, for example, a state where agency costs are projected to decrease significantly in the delayed maintenance scenarios, the health of the network declines from 89.2 percent in year 1 to 69.7 percent in year 10, a full 4.3 percent below where it would have been if maintenance was not delayed.

Figure 4.7 Change in Health Index for Selected Delayed Maintenance Scenarios – State 1

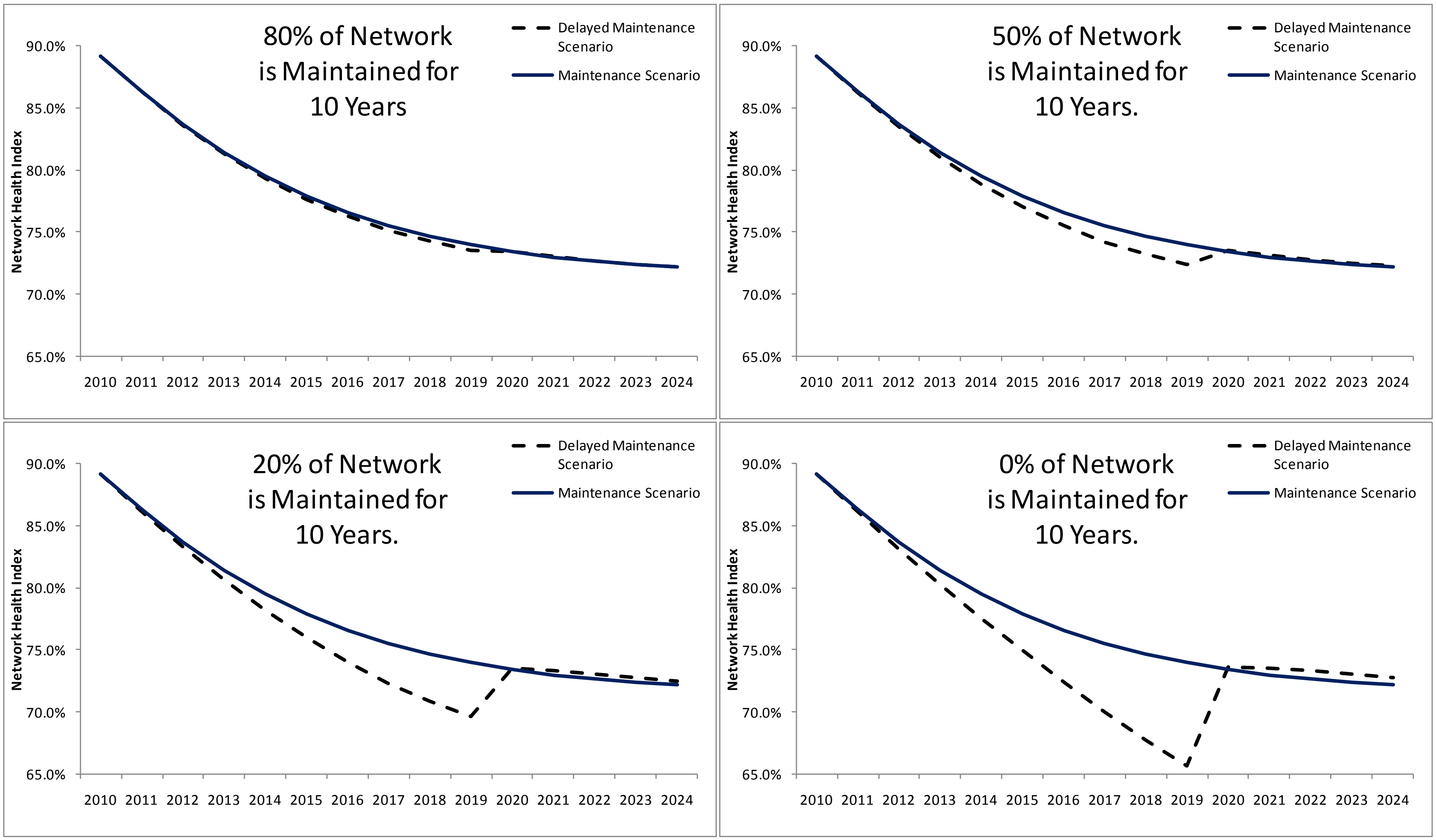


Table 4.6 Network Health Index for Selected Delayed Maintenance Scenarios

Health Index is recorded at the end of the delay duration

	Baseline Scenario	Selected Delayed Maintenance Scenarios (maintain X% of network)					
	100%	80%		50%		20%	
	Health Index	Health Index	Delta	Health Index	Delta	Health Index	Delta
State 1							
0 years	93.3%	93.3%	0.0%	93.3%	0.0%	93.3%	0.0%
5 years	89.9%	89.7%	-0.1%	89.4%	-0.4%	89.0%	-0.9%
10 years	87.1%	86.9%	-0.3%	86.2%	-0.9%	84.8%	-2.3%
State 2							
0 years	89.2%	89.2%	0.0%	89.2%	0.0%	89.2%	0.0%
5 years	79.5%	79.3%	-0.2%	78.8%	-0.7%	78.2%	-1.3%
10 years	74.0%	73.5%	-0.4%	72.4%	-1.6%	69.7%	-4.3%
State 3							
0 years	92.5%	92.5%	0.0%	92.5%	0.0%	92.5%	0.0%
5 years	86.1%	86.0%	-0.2%	85.6%	-0.5%	85.1%	-1.0%
10 years	81.3%	81.0%	-0.3%	80.2%	-1.1%	78.2%	-3.1%
State 4							
0 years	93.4%	93.4%	0.0%	93.4%	0.0%	93.4%	0.0%
5 years	89.7%	89.6%	-0.1%	89.4%	-0.3%	89.1%	-0.6%
10 years	86.8%	86.6%	-0.2%	86.1%	-0.7%	85.0%	-1.8%

5.0 Analyzing the Consequence of Delayed Pavement Maintenance

This section presents a methodology for estimating the consequence of delayed pavement maintenance. Conceptually, the approach is similar in nature to the bridge analysis approached described in the previous section. However the details of the two approaches very dramatically due to physical differences inherent between the two asset types, and in the state of the practice related to the evaluation of each. For example, for bridges, a national default maintenance work policy exists and performance measures have been established that can be calculated for every state DOT using existing data. For pavement, no such policy or performance measure exists. Therefore the pavement approach must include the development of these elements, where the bridge approach did not.

The pavement approach considers two main factors that influence the cost of deferred maintenance: 1) current and future pavement conditions, and 2) highway agency policies regarding past/future maintenance actions (i.e., availability of maintenance materials and placement equipment, maintenance action types considered, pavement condition that triggers intervention, service life of maintenance actions placed under prevailing site conditions). The approach is flexible enough to incorporate existing agency data and maintenance polices, rather than requiring any new or specific data collection or policy changes.

5.1 Overview of Approach

The main facets of the proposed approach are as follows:

1. Definition of pavement segment/corridor/network of interest for analysis.
2. Establishment of an analysis database using data from an agency's pavement management or other related databases that contain the following information for each pavement section:
   a. Pavement segment length and number of lanes;
   b. Current pavement type;
   c. Pavement section original construction, maintenance, and rehabilitation history (including last treatment type applied and year);
   d. Pavement section-specific distress and overall condition or smoothness;

   e. Costs associated with pavement maintenance, rehabilitation and repair (MR&R) actions (MR&R treatment application per lane mile, if available); and

   f. Rate of increase in pavement treatment cost through the deferred maintenance period.

3. Establishment of a procedure for modeling how fast individual pavement sections or the overall corridor/network deteriorate. This procedure includes the following steps:

   a. Define a family of pavements, based on:

      i. Pavement type;

      ii. Site conditions;

      iii. Design features;

      iv. Mix properties;

      v. Expected impact of previous maintenance actions on future pavement deterioration; and/or

      vi. Effects of agency business practices such as a preventive maintenance program on pavement deterioration rate.

   b. Select appropriate mathematical models for fitting observed performance data.

   c. Develop global distress/condition index performance models

4. Establishment of relationship between pavement condition and maintenance and rehabilitation needs, including:

   a. List of key pavement distresses that drive maintenance and rehabilitation related decision making;

   b. Information regarding agency standard pavement MR&R treatments and their average life expectancies; and

   c. Agency policy regarding acceptable threshold distress or condition indices level that trigger MR&R.

5. Creation of delayed maintenance cost estimation scenarios:

   a. "Agency MR&R Baseline" scenario:

      i. Engineering Decisions – Maintenance costs for MR&R applications based on the actual pavement conditions and agency set thresholds.

      ii. Policy Decisions - Maintenance costs for periodical MR&R applications based on agency policies.

      iii. Hybrid – Maintenance costs for MR&R applications based on both agency policies and actual pavement conditions.

b. "Delayed Maintenance" scenario: maintenance costs for delayed MR&R applications from a given reference year (mostly the current year) over a deferral period.

6. Estimation of the costs of delayed maintenance:

   a. Select appropriate baseline scenario based on agency practices.

   b. Select a deferral period (typically 1 to 5 years).

   c. Select analysis period (typically 10 to 15 years).

   d. Estimate baseline MR&R needs and associated costs in the current year and subsequent years (analysis period).

   e. Estimate MR&R needs and associated costs in the deferral year and subsequent years (analysis period).

   f. Consequence of delayed maintenance can be characterized as the difference in delayed and baseline maintenance costs.

More detail on each step is provided in the following sections.

5.2 Pavement Analysis Details

Step 1 Define Pavement Segment/Corridor/Network of Interest

The pavement segment/corridor/network of interest for analysis must be defined and described as follows:

- A pavement **segment** is a fundamental unit of roadway infrastructure that is identified in pavement management systems. Typically, it is a homogeneous length of roadway based on a set of physical properties. It is customary to divide highway corridors and networks into homogeneous segments, so that it may be assumed that, within each segment, the physical and other characteristics describing that segment are similar or the same and representative of the entire segment.
- A **corridor** generally is a linear part of a national or statewide highway system that provides mobility, connectivity to activity centers, connectivity to interstates, interstate relief routes, major hurricane evacuation routes, etc.
- A **network** is a combination of segments and corridors within an agency's jurisdiction.

Regardless of the extent of the highway or roadway being evaluated, the consequences of delayed maintenance are analyzed at the pavement segment level and aggregated at the network or corridor level. A segment typically represents a single pavement type. A corridor or network, however, could include several pavement types, new and rehabilitated. Thus, the pavement type

of interest is the predominant type of pavement within the highway corridor or network.

Step 2 Determine Inputs

The information essential to performing this analysis can be categorized as (1) data pertaining to pavement performance modeling, and (2) data pertaining to agency maintenance practices and associated costs. A description of the data types required is presented below.

Data Pertaining to Pavement Performance Modeling

Performance models are developed typically for a family of pavements in order to estimate future pavement performance for each pavement segment. Analysts must define the family of pavement types within a network or corridor for which performance models are required. As most agencies have some form of roadway/highway categorization schemes based on the highway functional class, traffic application level, pavement type, etc., these can be used for preliminary definition of families of pavements.

The basic definitions of a family can be refined to include factors known to impact pavement performance, such as climate, subgrade type (i.e., fine or coarse), asphalt concrete (AC) mix properties (conventional versus Superpave designs), and rigid pavement design properties (slab width, load transfer mechanism, steel content, and so on). Thus, typically, the data types listed in Table 5.1**Error! Reference source not found.** are required to define family of pavements.

Table 5.1 List of Data Types Required for Defining a Family of Pavements

Data Category	Example Variables
Inventory	Section identification, section length, begin and end milepost, longitude/latitude/elevation, year of last maintenance or rehabilitation event, categorical description of maintenance treatment type (e.g., none, non-structural, light, heavy), age since original construction or reconstruction, date and type of last pavement treatment performed
Pavement type	New conventional AC, new full-depth AC, new Jointed Plain Concrete Pavement (JPCP), new Continuously Reinforced Concrete Pavement (CRCP), AC overlaid existing AC, AC overlaid existing JPCP, etc.
Functional class	Interstate, US highway, urban freeways, county highways, local roads
Traffic application level	Less than 500 trucks per day, 500 to 1500 trucks per day, greater than 1500 trucks per day
Subgrade type	Fine, coarse
Climate	Wet, dry, freeze, nonfreeze
AC mix type	Marshall versus Superpave mix

Data Category	Example Variables
PCC design features	Doweled versus no dowelled JPCP JPCP with or without edge support

In addition to the data listed in Table 5.1**Error! Reference source not found.**, segment-specific historical performance data for the key pavement condition metric(s) are used in establishing the MR&R needs. Note that the approach for analyzing the consequence of delayed pavement maintenance assumes that MR&R needs and decisions are mostly driven by pavement condition. Thus, selecting appropriate condition metric(s) is a key step in performance modeling. Options for this step include:

- **Use the same overall pavement condition indices as used in pavement management to assess the need for maintenance and to forecast future needs.** The overall index in many agencies usually is a composite index that reflects the various surface distresses on the pavement and the ride quality of the pavement. These indices are calculated from either raw distress/smoothness data or other individual condition indices. Some advantages of this approach are that agency personnel already collect the required data to compute this index and indices used in this methodology are consistent with existing agency practices. A significant disadvantage is that it difficult to tie a specific maintenance action or set of maintenance actions to a trigger based on the overall condition index without losing accuracy. To make this approach work, maintenance and pavement management personnel need to evaluate historical data and come to a consensus regarding relationship between the overall condition indices and maintenance actions.
- **Use key pavement distresses rather than the overall pavement condition index** to trigger decision making with regard to maintenance actions. This scenario is a more fundamental *engineering approach* to maintenance. It assumes that key individual distresses are monitored and stored in the agency's pavement management system and that maintenance actions can be tied to specific distress levels. There is no limitation on the number of distresses that can be used by an agency for this purpose.

Note that, although maintenance and rehabilitation decisions are triggered mainly by current and future pavement condition, pavement condition-based decisions can be overridden by safety and user comfort concerns.

Data Pertaining to Maintenance Practices and Associated Costs

In addition to data required for performance modeling, the following maintenance and cost data are required:

1. MR&R treatment strategies and associated pavement condition thresholds (refer to Step 4);

2. Expected service life of each category of MR&R treatments, in years;
3. Maintenance deferral period (in years);
4. Analysis period in years;
5. The cost of various pavement treatments used by the agency; and
6. The percent of pavement maintenance funds to be deferred (as a percentage of total funds needed).

Step 3 Develop Performance Database and Models

As almost all pavement management systems have some capability to predict future pavement condition or contain guidance on the expected life of new and rehabilitated pavements and MR&R actions, agencies usually can simply adopt the pavement condition forecasting tool available and apply as needed with this methodology. Otherwise, they may follow the following procedure for forecasting future pavement condition.

Development of Pavement Performance Database

The assembled analysis database can be used to develop a pavement performance database. Typically, input variables can be obtained from the agency pavement management database and other relevant databases (e.g., traffic, construction, maintenance). As agency databases typically contain far more information than required for performance model development, the first step in developing a performance database for model development is to review the available databases and identifies data variables required for:

- Defining families of pavements (mostly inventory, traffic, soil maps, and climate type data);
- Defining pavement type and original construction and MR&R treatment dates (construction, maintenance, and rehabilitation data); and
- Characterizing pavement condition (rutting, transverse cracking, and roughness).

Definition of Pavement Type and Family

The historic pavement segment construction, maintenance, and rehabilitation data available in the assembled analysis database must be used to construct for each unique pavement segment a history of significant pavement construction and MR&R activities. Once the pavement layer history is established, analysts can define current and past pavement types and corresponding placement and removal timelines of each pavement type for a given pavement segment.

Using the assigned pavement types and other pertinent information, such as climate, subgrade type, traffic application level, design features, and AC mix properties for each pavement segment, analysts can group all pavement segments within the corridor or network into families of the same pavement

type, similar MR&R history, and similar site conditions (climate, subgrade, traffic). Note that AC mix properties and design features can be included in the definition of pavement type. It is expected that pavement segments within the same families will exhibit similar performance characteristics.

Review of Assembled Performance Data

The assembled performance data must be reviewed for reasonableness of the condition indices, distresses, and smoothness values and their trends. Reasonableness is defined as having values within typical expected range (e.g., rut depth ranging from 0 to 1.5 in). Reasonableness of trends implies that a plot of, for example, International Roughness Index (IRI) versus age will show a gradual increase in IRI with increasing pavement age. A significant decrease in IRI over time would be deemed as potentially erroneous. Data deemed as outliers or erroneous must be corrected or removed from the analysis database prior to analysis.

Development of Performance Models

Performance models must be developed for each family of pavements. The first step in model development is to select an appropriate mathematical equation (model form) that best describes the progression of the given performance metric with age or traffic applications. Examples of mathematical equations commonly used to fit pavement performance data are presented below:

Linear: $PM = \alpha + \beta * AGE$ (1)

Polynomial: $PM = \alpha + \beta AGE + \chi AGE^2 + \ldots\ldots\ldots\ldots \gamma AGE^n$ (2)

Power: $PM = \alpha AGE^{\beta}$ (3)

Exponential: $PM = \alpha e^{\beta * AGE}$ (4)

where

PM = performance metric

AGE = pavement age in years

$\alpha, \beta, \chi, \gamma$ = regression constants

The model form typically is selected by reviewing trends from plots of measured performance metrics versus age and selecting the mathematical equation that best fits the observed trend.

Following the selection of the best mathematical equation, linear or nonlinear statistical regression techniques must be applied to fit the selected mathematical equation to the measured performance data. This typically involves determining the values of regression constants for any of the selected mathematical equations that cause the equation to best fit observed performance data. Best fit can be determined using diagnostic statistics such as coefficient of determination (R^2) and sum of error estimate (SEE).

Although performance models can be developed for each metric on a segment by segment basis, for this methodology the following approach is recommended:

- For a given performance metric, develop "global" models for the predefined family of pavements or select an appropriate agency performance prediction models (used in the pavement management system);
- Apply appropriate "global" models developed as needed on a segment by segment basis; and
- Where actual measured performance data are available for a given pavement segment, use the actual measured data to adjust the global model predictions as needed.

Step 4 Establish a Relationship between Pavement Condition and MR&R Needs

A key aspect of this methodology is the establishment of a relationship between MR&R needs and actual pavement condition characterized by extent and severity of distress/roughness present on the pavement surface. To develop sound and accurate estimates of cost of delayed maintenance, this relationship must be developed based on both agency MR&R decision trees and actual practice in the field, as reflected in the agency pavement management and MR&R databases.

An example of an MR&R decision tree for California statewide local streets and roads is presented in Table 5.2. Note that the recommendations presented the table must be adjusted as needed to reflect when MR&R treatments are actually placed, as agencies do not always follow their own recommendations to the letter, for reasons ranging from in adequate budgets to lack of personnel.

Table 5.2 Example Pavement Condition Index Maintenance Thresholds

Maintenance Treatment	PCI Thresholds	
	Rural	Urban
Do nothing	86-100	75-100
Preventive maintenance(e.g., surface seal, slurry seal, cape seal)	70-85	60-75
Thin AC overlay	50-70	40-60
Thick AC overlay	25-50	0-40
Reconstruction	0-25	Never

Source: California Statewide Local Streets and Roads Needs Assessment, 2009

Step 5 Establish MR&R Costs

Another critical aspect of assessing the consequence of delayed maintenance is establishing best possible estimates of unit prices for the various pay items (materials, labor, equipment, etc.) associated with MR&R treatments. This goes a long way toward ensuring a more accurate assessment of delayed maintenance costs.

Typically, unit cost data are obtained from multiple sources within an agency. The raw cost data must be checked and corrected, as necessary, to ensure the highest level of confidence. Cost data checks must include the following:

- Cost data should be representative of the geographic region and project size;
- Unit prices can be obtained from historical bid data of MR&R projects undertaken within the last 5 to 7 years;
- Average unit prices must be adjusted to the present day to account for effects of inflation; and
- Cost-based estimation can be used when the historical bid-based estimates are not available or defendable.

Table 5.3 presents an example cost estimates for MR&R treatments used in California.

Table 5.3 Example of Pavement MR&R Treatments Cost Estimates

Maintenance Treatment	Cost Estimate (2009)
Do nothing	\$0.00
Preventive maintenance(e.g., surface seal, slurry seal, cape seal)	\$2.70 to 2.80 per yd^2
Thin AC overlay	\$17.90 to \$29.10 per yd^2
Thick AC overlay	\$26.40 to \$29.10 per yd^2
Reconstruction	\$61.20 to \$91.80 per yd^2

Source: California Statewide Local Streets and Roads Needs Assessment, 2009

Step 6 Estimate Cost of Delayed Maintenance

The procedure for estimating the cost of delayed maintenance is presented below.

Step 6.1 Select a Baseline Scenario for the Analysis Based on Typical Agency Practices

An agency baseline scenario based on typical MR&R practices can be created using one of the following approaches:

- **Engineering Decisions.** Under this scenario, the selection of MR&R treatments and intervention timing is based on the actual/forecasted pavement conditions and agency set thresholds.
- **Policy Decisions.** Under this scenario, the selection of MR&R treatments and intervention timing is based on agency policy alone.
- **Hybrid.** The selection of MR&R treatments and intervention timing is based on agency policies, funding constraints, and actual pavement conditions.

Step 6.2 Select a Deferral Period

A delayed maintenance scenario can be developed by deferring the baseline MR&R strategy from a given reference year (usually the current year) over a deferral period. Typically, pavement MR&R actions are deferred up to 5 years.

Step 6.3 Select an Analysis Period

MR&R treatments typically are selected based on the actual or predicted performance metrics that describe the pavement condition. The purpose of the MR&R treatment application can be routine, preventive, or corrective in nature. The effectiveness of MR&R treatments usually differs due to differences in the treatment type, timing, and extent of application. Hence, it is necessary to evaluate the consequences of maintenance delay over a sufficiently long time to incorporate any differences in the effectiveness of both immediate and subsequent treatment applications. An analysis period of 10 to 15 years is reasonable to capture these differences.

Step 6.4 Estimate MR&R Needs and Associated Costs for the Baseline Scenario

MR&R needs and associated costs can be determined as follows:

- Forecast pavement conditions over the analysis period using the approach discussed in step 3;
- Compare the predicted conditions with agency thresholds that trigger MR&R actions;
- Identify the intervention year and MR&R needs using the approach discussed in step 4;
- Reset the pavement condition after every MR&R intervention as needed (e.g., post-treatment rutting values can be reset to zero after placing a hot mix asphalt overlay);
- Establish the sequence of specific MR&R actions and corresponding intervention timing over the analysis period; and
- Establish MR&R strategy costs streams. The costs associated with each MR&R action should be estimated using the approach discussed in step 5.

The estimated costs should be converted to a reference year by applying appropriate discount factors.

Step 6.5 Estimate MR&R Needs and Associated Costs for the Delay Scenario

This step involves using several "what if "scenarios to evaluate the MR&R needs if the MR&R intervention is delayed. Typical scenarios include deferring the MR&R schedule for up to 5 years in 1-year increments. The effects of the MR&R deferral on MR&R needs and costs can be simulated for each scenario as needed, using the same approach outlined in the previous step.

Step 6.6 Evaluate the Consequence of Delayed Maintenance

The consequences of delayed maintenance can be assessed in terms of percent change and absolute difference in MR&R costs over a given analysis period when compared to the baseline scenario. The consequences of delayed maintenance can be evaluated first at the roadway segment level and later aggregated to quantify overall consequences at the corridor or network level.

5.3 PROTOTYPE TOOL

The research team automated the approach described above in a macro-enabled, Visual Basic Application (VBA) based spreadsheet tool. This tool is designed to estimate MR&R needs and the associated costs of various delayed maintenance scenarios. This prototype tool possesses some of the capabilities of a pavement management software system, such as the deterministic projection of pavement conditions using pavement performance models, identification of MR&R needs, and estimation of associated costs. It was developed to demonstrate the feasibility of the methodology presented herein. Thus, the tool has the following limitations:

- The mathematical form of the pavement deterioration models is fixed and cannot be modified. However, the model coefficients can be modified as needed.
- The tool cannot consider more than three pavement performance metrics.
- The tool can consider up to four MR&R treatments within an analysis cycle.
- While MR&R triggers can be changed, the decision table used in this tool is based on Kansas DOT practices.

The key general features of this tool are as follows:

- **Inputs**
  - General inputs - users are required to enter basic inputs for the analysis such as the current year, deferral year, and analysis period (see Figure 1).

- Agency-specific inputs - this worksheet includes various information tables used by an agency, such as the treatment matrix, cost per mile for each treatment type, Office of Management and Budget (OMB) discount rates, pavement performance models for up to three performance metrics, thresholds for engineering interventions, etc. (See Figures 5.2 and 5.3).

- **Pre-processing** — using these worksheets, a user can make necessary adjustments to the global coefficients of the pavement performance models to roadway segment-specific conditions. Multiple worksheets are provided for various pavement condition parameters.
- **Baseline and delay scenarios** – these worksheets are used to simulate the effects in terms of MR&R needs and costs for both baseline and delayed maintenance scenarios.
- **Outputs** – this worksheet presents the cost outputs for both baseline and delay scenarios. Plots of the consequence of delayed maintenance are presented in terms of percent change and absolute difference in MR&R costs (see Figures 5.4 and 5.5).

A demonstration of the prototype tool is presented in section 5.5.

Figure 5.1 General Input Screen of the Prototype Tool

NCHRP 14-20 Consequences of Delayed Maintenance	
Current Year	2011
Year of Deferral	2015
Analysis Period	15
End of Analysis Period	2026
15-year Discount Rate (OMB A-94)	1.30%

Figure 5.2 Example of User-Defined Pavement Performance Prediction Model Parameters used in the Prototype tool

IRI Models			
Pavement Type	Maintenance Level	Intercept	Slope
HMA/FDAC	Original	42.2	0.165
HMA/FDAC	Reconstruction	42.2	0.165
HMA/FDAC	Heavy	43.6	0.237
HMA/FDAC	Light	42.6	0.369
HMA/FDAC	Non-Structural	46.9	0.258

Transverse Cracking Models			
Pavement Type	Maintenance Level	Intercept	Slope
HMA/FDAC	Original	0.83	1.444
HMA/FDAC	Reconstruction	0.83	1.444
HMA/FDAC	Heavy	4.30	1.101
HMA/FDAC	Light	17.20	0.756
HMA/FDAC	Non-Structural	17.09	0.812

Rutting Models			
Pavement Type	Maintenance Level	Intercept	Slope
HMA/FDAC	Original	0.09	0.157
HMA/FDAC	Reconstruction	0.09	0.157
HMA/FDAC	Heavy	0.11	0.166
HMA/FDAC	Light	0.09	0.218
HMA/FDAC	Non-Structural	0.07	0.539

Figure 5.3 Examples of User-defined Cost and Expected Service Life Information used in the Prototype Tool

Potential Maintenance Treatments and Costs				
No.	Pavement Treatment	Cost per Lane Mile	Maintenance Level	Expected Service Life
1	Crack Sealing (0-50)	$4,000	Non-Structural	3
2	Crack Sealing (50-100)	$5,000	Non-Structural	3
3	Crack Sealing (100+)	$6,000	Non-Structural	3
8	Microsurfacing	$32,000	Non-Structural	6
10	HMA Overlay (< 1 inch)	$40,000	Non-Structural	6
12	Cold Milling (> 1 inch)	$6,000	Light	6
14	Surface Recycling (2 inch)	$37,000	Light	5
15	HMA Overlay (1½ inch)	$50,000	Light	6

Figure 5.4 Example Corridor-wide MR&R Expenditure Stream Outlay Created by the Prototype Tool

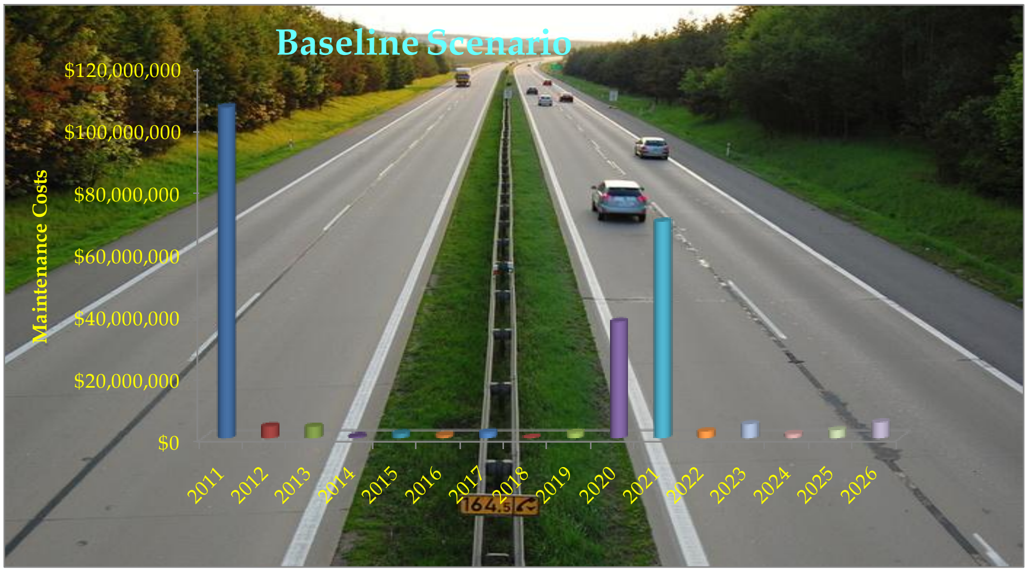
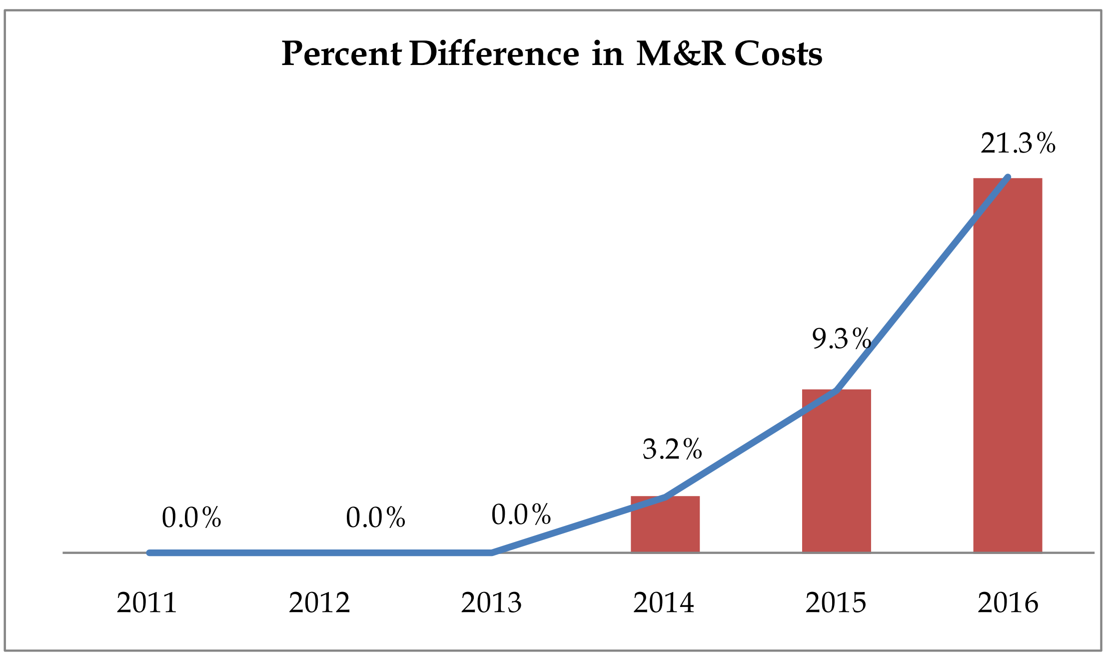


Figure 5.5 Example Cost Comparison of Baseline and Delayed MR&R Scenarios Created by the Prototype Tool



5.4 RESULTS OF PILOT APPLICATION

This section describes a pilot application of the analysis approach described in the previous section. The nature of the pavement pilot effort differed significantly from that of the bridge pilot described in Section 4. Given the availability of national defaults for key data and models, the bridge pilot analyzed 101 maintenance scenarios for 4 states. In contrast, because of the lack of national defaults, the pavement pilot had significantly more depth, but less breadth relative to the bridge pilot. The objective of the pavement pilot is to show how an agency could, step-by-step, implement the pavement analysis approach described above.

Step 1 Define the Pavement Segment/Corridor/Network of Interest for Analysis

One of the goals of the pilot was to demonstrate the general capabilities of the prototype tool by applying it to roadway corridors with different pavement types, traffic levels, and existing condition levels, and subjected to various MR&R treatments. The criteria for selecting a roadway corridor for the pilot case study were as follows:

- Pavement types;
- Construction and MR&R history;
- Traffic level; and
- Existing pavement conditions.

To satisfy these criteria, two highway corridors in Kansas were selected for the pilot case study (see Figure 5.6): Interstate 70 (I-70) and U.S. highway 400 (US-400). Both of these highways run east to west across Kansas. I-70 is approximately 424 miles long, while US-400 is approximately 440 miles. A 366-mile portion of I-70 and 164-mile portion of US 400 were selected for analysis.

Figure 5.6 Map showing Interstate 70 and US 400 highway corridors across Kansas

The distributions of heavy commercial truck traffic on the selected highway corridors are shown in Figures 5.7 and 5.8. As shown, I-70 experiences significantly higher traffic levels (1,200 to 2,400 with a mean of 1,779 trucks per day) than US-400 (100 to 550 with a mean of 3,789 trucks per day). The corridors span across 24 counties and 6 Kansas Department of Transportation (DOT) districts.

Figure 5.7 Distribution of heavy commercial truck traffic on selected portions of I-70

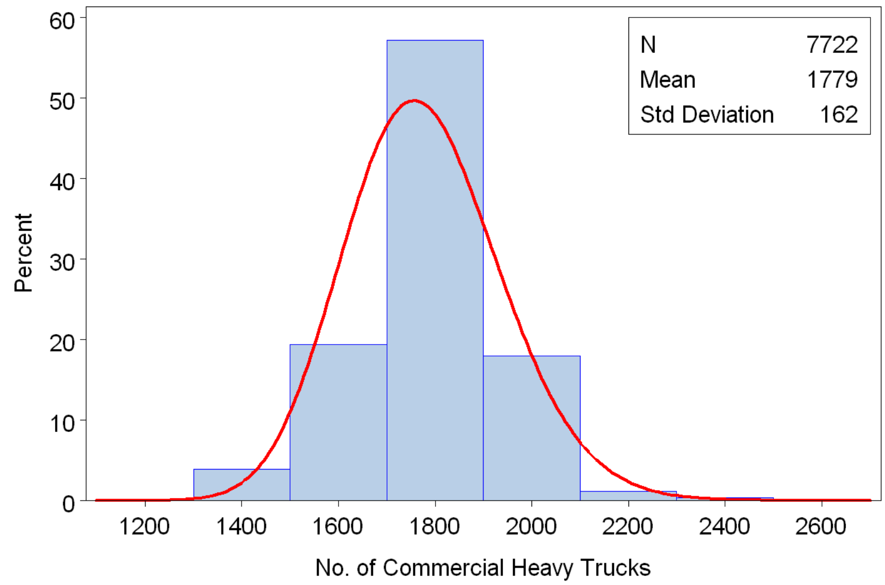
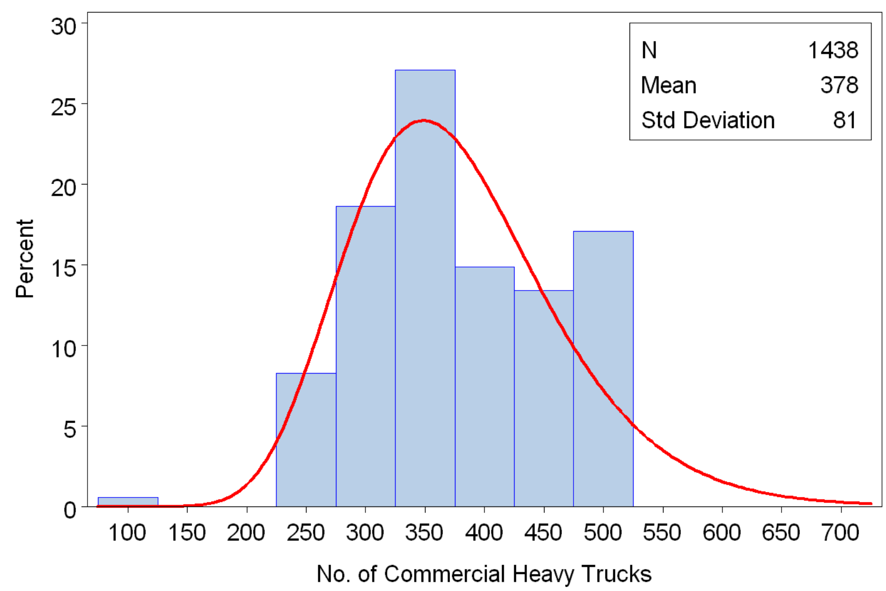


Figure 5.8 Distribution of heavy commercial truck traffic on selected portions of I-400



Step 2 Determine Inputs

Inputs for developing an analysis database were obtained from the Kansas DOT PMIS and CANSYS databases. The first step in developing a project database for model development was to review the entire PMIS database and identify data items required for model development. The data items required mostly pertained to the following:

- Inventory data required for defining analysis cells;
- Construction and MR&R data required for defining pavement type and original construction and MR&R treatment dates;
- Performance data (rutting, transverse cracking, and IRI) for characterizing pavement condition;

Key data items identified and assembled included:

- PMISID: Pavement section ID number.
- RDCAT: Roadway category.
- CATDESC: Roadway category description.
- CLASS: I: for interstate. O: for all others.
- PVMT: Asphalt pavement.
- PCCP: Portland cement concrete pavement.
- COMP: Composite pavement, PCC pavement or brick that has been overlaid with asphalt concrete.
- FDBIT: Full design bituminous pavement, designed and constructed to carry expected traffic.
- PDBIT: Partial design bituminous pavement, not designed or constructed to carry expected traffic.
- COUNTY: 001 to 105 Corresponding county name and county abbreviation
- RTTY: Route Type 1=Interstate, 2=US-Route and 3=K Route (character 4 of PMISID).
- RTNO: Route Number.
- DIR: Direction of travel.
- LANE: 0=undivided, 1=west bound, 2=north bound, 3=east bound, & 4=south bound.
- MPBEG: Begin Milepost.
- MPEND: End milepost.
- DISTRICT: District # 1 through 6 (1=NE, 2=NC, 3=NW, 4=SE, 5=SC, & 6=SW).
- LRS_KEY: Agency standard linear referencing. Similar to PMISID.

Also identified and assembled were performance metrics (distress and IRI data) as needed. All data were assembled into a project database in spreadsheet format. Key data items used as identifiers of pavement segments within the corridors were PMISID, MPBEG, MPEND, RTTY, DIR, and RTNO.

Develop Pavement Layer History and Define Pavement Type

The historic pavement layer placement and removal information in the CANSYS Pavement Layer History data table was used to construct for each unique pavement section defined by PMISID, MPBEG, MPEND, RTTY, DIR, and RTNO data items a history of significant pavement construction and MR&R activities. An example is presented for PMISID 0082400018190 in Table 5.4.

Once the pavement layer history was established, appropriate pavement types descriptions were assigned to each pavement segment (see Table 5.5).

Table 5.4 Example Pavement Layer Placement History Obtained from Kansas DOT Databases

ID	Begin MP	End MP	Dir	Rt. No.	Placement Year	Thickness, (inches)	Pavement Type	MR&R Activity Type	Beg. Date	End Date
0082400018190	302.31	304.05	EB	400	1985	6	FDAC	Original	1985	1991
0082400018190	302.31	304.05	EB	400	1991	1	HMA/FDAC	N	1991	2000
0082400018190	302.31	304.05	EB	400	2000	3	HMA/FDAC	L	2000	2005
0082400018190	302.31	304.05	EB	400	2005	0	M1	N	2005	2011

Table 5.5 Example Pavement Type Definition Obtained for Pilot

ID	Begin MP	End MP	Dir	Rt No.	Thickness, (inches)	Pavement Type	MR&R Activity Type	History
0082400018190	302.30	304.05	EB	400	1	AC/FDAC	L	AC/FDAC 3-in (non-structural) from 1996 to 2000
0082400018190	302.30	304.05	EB	400	3	AC/FDAC	L	AC/FDAC 3-in (light-structural) from 2000 to 2005

Both I-70 and US-400 include various new and rehabilitated pavement types. The breakdown of pavement types was as follows:

- I-70
  - Approximately 60 percent of the corridor was new or overlaid AC pavement (including mill and overlay).
  - The remaining 40 percent were mostly new doweled jointed plain concrete pavement (JPCP), with some portions subject to maintenance, joint repairs, and AC overlays.
- US-400
  - Approximately 21 percent of the corridor was new or AC overlaid (including mill and overlay) asphalt pavement.
  - The remaining 40 percent were mostly new doweled JPCP with some portions subject to maintenance, joint repairs, and AC overlays and jointed reinforced concrete pavement (JRCP).

The typical full depth AC (FDAC) pavement on both corridors had an AC thickness ranging from 11 to 14 inches placed directly over a prepared subgrade. The typical JPCP had a thickness of 12 to 13 inches of PCC over a prepared base and subgrade. A review of the existing pavements structure, design features, and MR&R history was done to help categorize and define the pavement types on the two corridors as follows:

- New pavements
  - Conventional Asphalt Concrete (CAC)—Relatively thin AC layer placed on relatively thick untreated aggregate base course and prepared subgrade. The criteria used to define CAC pavements were that the total asphalt layer thickness had to be less than 7.5 in and could constitute no more than 40 percent of the total structure thickness (i.e., combined thickness of asphalt surface and aggregate base/subbase).
  - FDAC—Current flexible design standard consisting of thick AC layer (surface and hot mix asphalt or asphalt-treated base) placed on prepared or modified (cement-, lime, or other treated) subgrade.
  - JRCP (Doweled)—Primarily steel mesh-reinforced concrete with dowels and 61.5-ft joint spacing, placed on unbound aggregate and prepared subgrade. The dowel bars are used to enhance load transfer at transverse joints.
  - JPCP (Doweled)—Current rigid design standard consisting primarily of doweled concrete with 15-ft perpendicular joint spacing, placed on cement- or aggregate-treated base and prepared or modified subgrade.

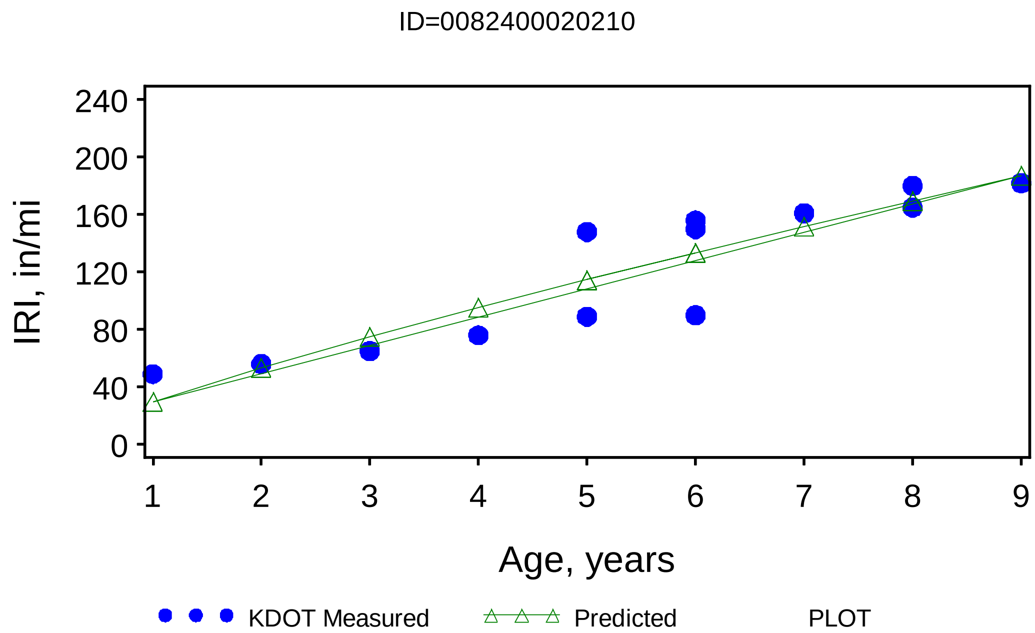
- MR&R activities (as defined and described by Kansas DOT)
  - Non-Structural (N)—maintenance treatments, such as chip seals, slurry seals, and crack sealing that add little if any structural capacity to the pavement. Essentially, these treatments are less than 1.5 in thick.
  - Light (L)—Major maintenance or minor rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or minor concrete pavement restoration (CPR, e.g., limited patching with or without diamond grinding) on rigid pavements, that add some structure to the pavement and significantly improve the ride quality and other functional characteristics. With the exception of minor CPR, these treatments typically range in thickness between 1.5 and 3.0 in.
  - Heavy (H)—Major rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or major CPR (dowel bar retrofit or extensive patching, followed by diamond grinding) on concrete pavements, that add substantial structure to the pavement, while also improving functional characteristics. With the exception of major CPR, these treatments are essentially greater than 3.0 in thick.

The research team combined both new pavement and MR&R activities definitions to define pavement type for analysis (e.g., CAC-N—a CAC subjected to a non-structural rehabilitation activity). Although the predominant pavement types on the selected corridors were FDAC and doweled jointed plain concrete (JPC-D), only the new and rehabilitated flexible pavement portions of the selected corridors were included in the analysis.

Data Pertaining to Pavement Performance Modeling

KDOT uses rutting, transverse cracking and IRI as performance metrics for making MR&R decisions. For each pavement segment selected in this pilot study, historical performance data were collected and assembled for these performance metrics. The assembled performance data was reviewed for reasonableness by reviewing their magnitude and trends. For example, Figure 5.9 shows a plot of IRI versus age for PMIS 0082400020210. The plot shows a reasonable increase in IRI with increasing pavement age. Also, the magnitude of IRI was deemed as reasonable. Data deemed as outliers or erroneous were removed from the database.

Figure 5.9 Plot of IRI Versus Age for PMIS 0082400020210)



Step 3 Develop Performance Database and Models

Prediction models were developed for each performance metric and family of pavements using the Kansas DOT performance data (see Table 5.6**Error! Reference source not found.**). The first step in model development was to select an appropriate model form (linear or nonlinear) and a mathematical equation that best describes the selected model form.

The model form was selected by reviewing trends from plots of measured distress/IRI versus age. The review indicated that for all distress/IRI types of interest, the distress/IRI versus age relationship was nonlinear.

Table 5.6 Performance Models Developed for the Pilot

Pavement Type	Maintenance Type	IRI	Transverse Cracking	Rutting
FDAC	Original/ Reconstruction	✓	✓	✓
HMA/FDAC	Heavy	✓	✓	✓
HMA/FDAC	Light	✓	✓	✓
HMA/FDAC	Non-Structural	✓	✓	✓

Several mathematical equations were reviewed to determine the one that fitted the observed nonlinear trends best (logarithmic, exponential, polynomial, power, etc.). The most appropriate mathematical equation was a nonlinear power equation as shown below:

$$PM = a(AGE)^b \tag{5}$$

where

PM	=	rutting, transverse cracking, or IRI
AGE	=	pavement age in years
a, b	=	regression constants

Using the selected mathematical equation, distress/IRI prediction models were developed as follows:

- For a given family of pavements, all available rutting and transverse cracking distress data were combined and a single "global" model was developed.
- For IRI, because post MR&R treatment placement IRI values could be significantly different, models were developed independently for each pavement segment. The mean model parameters a and b for each family of pavements were then used as representative values.

The final transverse cracking, rutting, and IRI prediction models are presented in Tables 5.7 through 5.9. Figures 5.10 through 5.12 show predicted transverse cracking, rutting, and IRI using the final models. The model statistics summarized in Figure 5.13 are reasonable for the kind of analysis performed.

Figures 5.10 through 5.12 also show reasonable trends, with FDAC subjected to heavy structural MR&R exhibiting the lowest deterioration rates while FDAC subjected to non-structural MR&R exhibited the highest deterioration rates.

Table 5.7 Summary of the Transverse Cracking Models Coefficients

	Analysis Cell			
Model Coefficients	**FDAC Original**	**Heavy-Structural**	**Light-Structural**	**Non-Structural**
a	0.82958	4.29633	17.20183	17.08808
b	1.44429	1.10094	0.75556	0.81186
Model Statistics				
R^2	0.0630	0.1462	0.2085	0.1785
SEE (cracks per mile)	102	149	288	291
N	246	1038	219	402

Table 5.8 Summary of the Rutting Model Coefficients

	Analysis Cell			
Model Coefficients	**FDAC Original**	**Heavy-Structural**	**Light-Structural**	**Non-Structural**
a	0.09239	0.10786	0.09367	0.07256
b	0.15673	0.16598	0.2175	0.53868
Model Statistics				
R^2	0.065	0.1324	0.2690	0.2800
SEE (inches)	0.02231	0.02153	0.02750	0.02715
N	541	37	139	162

Table 5.9 Summary of the IRI Model Coefficients

	Analysis Cell			
Model Coefficients	**FDAC Original**	**Heavy-Structural**	**Light-Structural**	**Non-Structural**
a	42.2	43.6	42.6	46.9
b	0.1649	0.2368	0.3694	0.2577
Model Statistics				
R^2	0.3319	0.2260	0.3731	0.4977
SEE (inches/mile)	4.57267	7.63519	14.89469	7.83801
N	374	1559	357	604

Figure 5.10 Predicted Transverse Cracking for Different Pavement Types

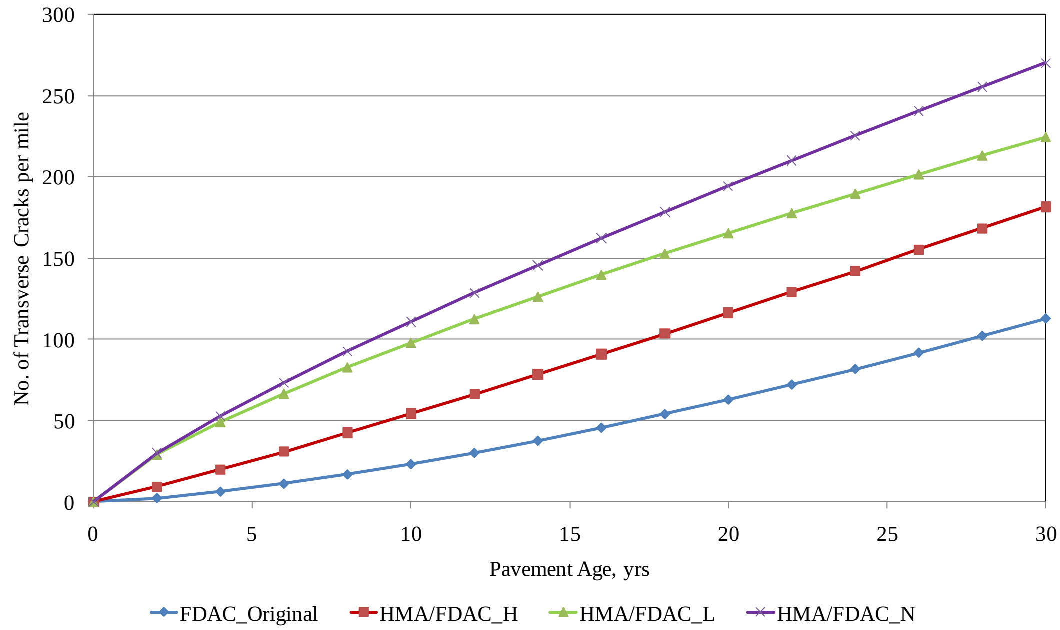


Figure 5.11 Predicted Rutting for Different Pavement Types

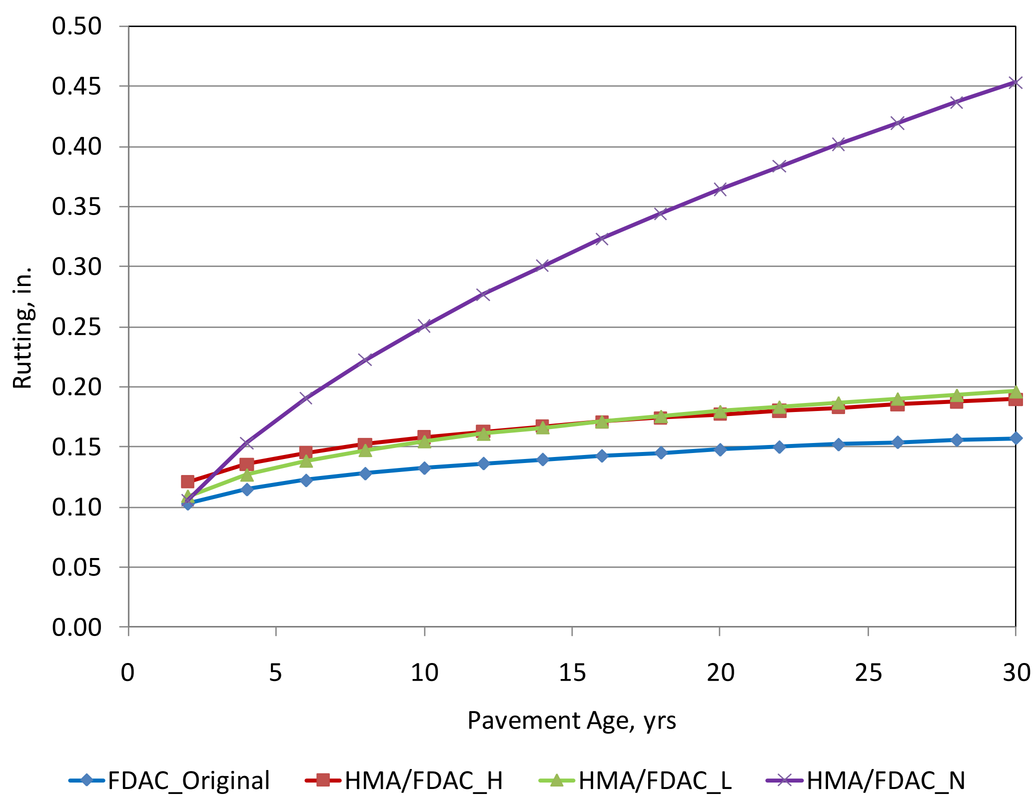


Figure 5.12 Predicted IRI for Different Pavement Types

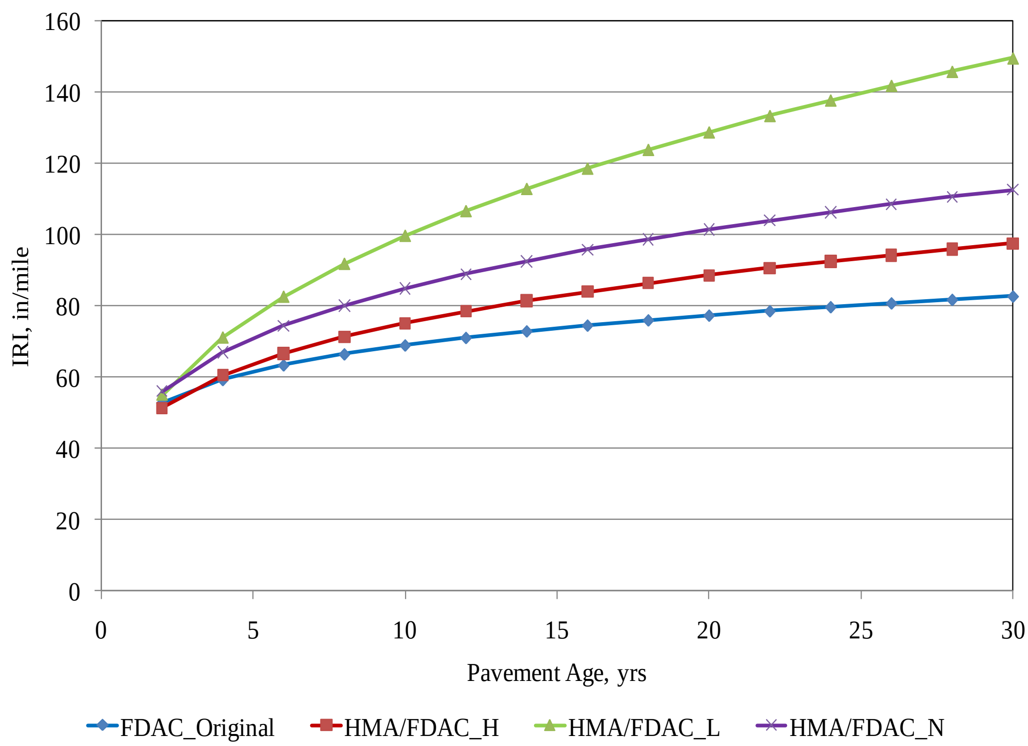
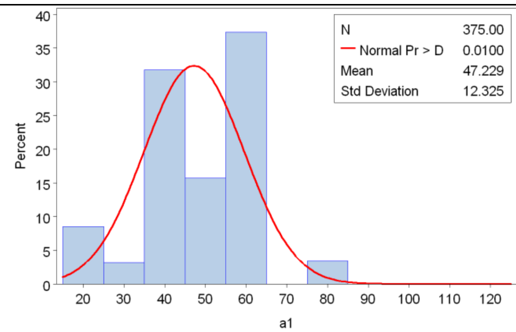
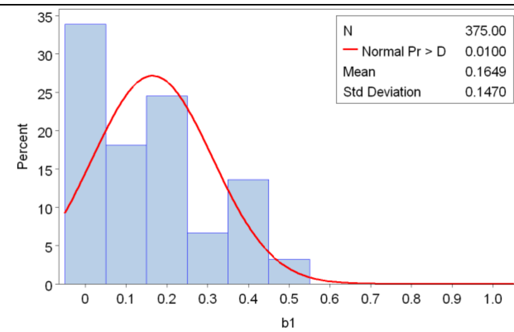


Figure 5.13 Regression Statistics of the Global Performance Models

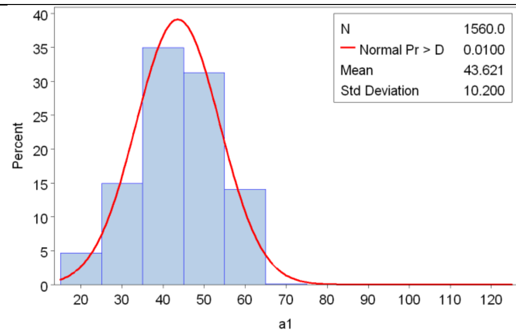


(distribution of regression coefficient, a)



(distribution of regression coefficient, b)

FDAC Original



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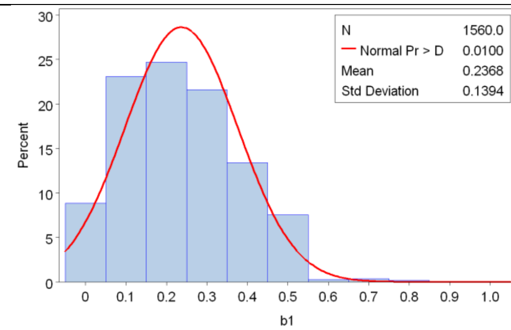
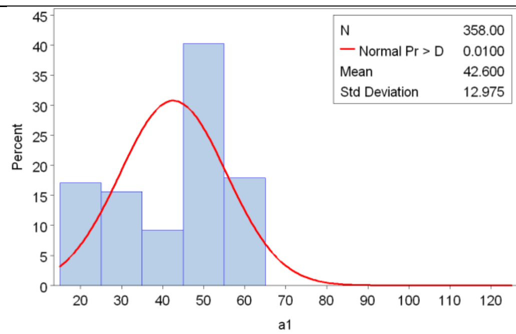


(distribution of regression coefficient, b)

FDAC Heavy-Structural



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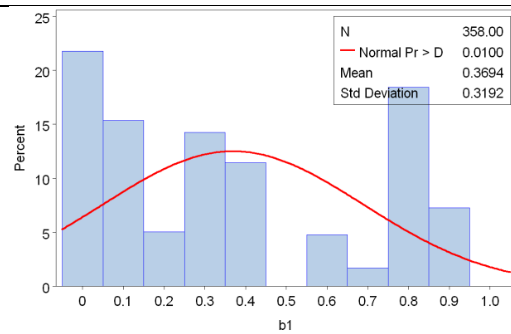
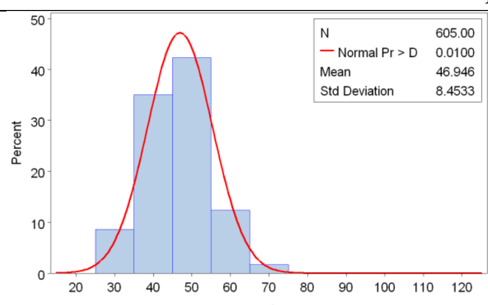


(distribution of regression coefficient, b)

FDAC Light-Structural



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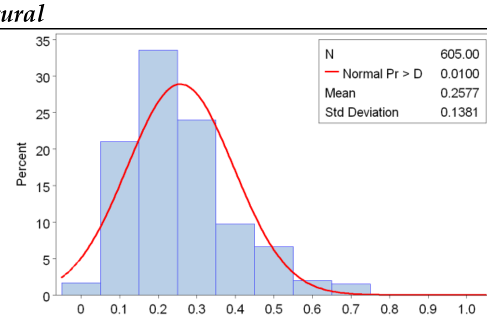


(distribution of regression coefficient, b)

FDAC Non-Structural

Step 4 Establish a Relationship between Pavement Condition and MR&R Needs

In the pilot application, Kansas DOT's maintenance treatment selection matrix was used to identify appropriate MR&R treatment strategies and performance thresholds that trigger MR&R intervention (see Table 5.10). Kansas's MR&R decision matrix is based on traffic volume (average annual daily traffic (AADT) ≤ 5000 or > 5000), pavement age since last maintenance treatment (0-3, 4-7 and 8+ years), average rutting (0-0.5, 0.5-1.0, >1 in), IRI (< 95, 95-170, 170-220 in/mile), and number of transverse cracks per mile (0-50, 50-100, >100).

Table 5.10 Kansas DOT Maintenance Treatment Matrix

Age Since Last Treatment	Transverse (cracks/mile)	Average IRI* (in/mile)	Average Rutting (in)	Recommended Treatment Strategy
0-3	0-50	0-94	0-0.5	None
0-3	0-50	0-94	0.5-1	Crack Sealing (0-50), Microsurfacing
0-3	0-50	0-94	> 1	Crack Sealing (0-50), Chip Seal Coat (Polymer Modified Asphalt), Microsurfacing (Ruts Only)
0-3	0-50	95-170	0-0.5	Surface Recycling (1 in.)
0-3	0-50	95-170	0.5-1	Crack Sealing (0-50), Microsurfacing
0-3	0-50	95-170	> 1	Cold Milling (> 1 in.), Crack Sealing (0-50), HMA Overlay (1½ in.)
0-3	0-50	170-220	0-0.5	Surface Recycling (1 in.), Chip Seal Coat (Polymer Modified Asphalt),
0-3	0-50	170-220	0.5-1	Crack Sealing (0-50), Microsurfacing (Ruts Only)HMA Overlay (< 1 in.)
0-3	0-50	170-220	> 1	Reconstruction-Surface Only
0-3	50-100	0-94	0-0.5	Crack Sealing (50-100)
0-3	50-100	0-94	0.5-1	Crack Sealing (50-100), Microsurfacing
0-3	50-100	0-94	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), Chip Seal Coat (Polymer Modified Asphalt)
0-3	50-100	95-170	0-0.5	Surface Recycling (1 in.), Chip Seal Coat (Polymer Modified Asphalt)
0-3	50-100	95-170	0.5-1	Surface Recycling (1 in.), HMA Overlay (< 1 in.)
0-3	50-100	95-170	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
0-3	50-100	170-220	0-0.5	Cold Milling (½ - 1 in.), Crack Sealing (50-100), HMA Overlay (< 1 in.)
0-3	50-100	170-220	0.5-1	Surface Recycling (1 in.), HMA Overlay (1½ in.)
0-3	50-100	170-220	> 1	Reconstruction-Surface Only

Age Since Last Treatment	Transverse (cracks/mile)	Average IRI* (in/mile)	Average Rutting (in)	Recommended Treatment Strategy
0-3	>100	0-94	0-0.5	Crack Sealing (100+)
0-3	>100	0-94	0.5-1	Crack Sealing (100+), Microsurfacing
0-3	>100	0-94	> 1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
0-3	>100	95-170	0-0.5	Surface Recycling (1 in.), HMA Overlay (1½ in.)
0-3	>100	95-170	0.5-1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
0-3	>100	95-170	> 1	Reconstruction-Surface Only
0-3	>100	170-220	0-0.5	Cold Milling (> 1 in.), Crack Sealing (100+), HMA Overlay (1½ in.)
0-3	>100	170-220	0.5-1	Reconstruction-Surface Only
0-3	>100	170-220	> 1	Reconstruction-Surface Only
4-7	0-50	0-94	0-0.5	Crack Sealing (0-50), HMA Overlay (2 in.)
4-7	0-50	0-94	0.5-1	Crack Sealing (0-50), Microsurfacing
4-7	0-50	0-94	> 1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (< 1 in.)
4-7	0-50	95-170	0-0.5	Surface Recycling (1 in.), Chip Seal Coat (Polymer Modified Asphalt)
4-7	0-50	95-170	0.5-1	Surface Recycling (1 in.), HMA Overlay (< 1 in.)
4-7	0-50	95-170	> 1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
4-7	0-50	170-220	0-0.5	Cold Milling (> 1 in.), Crack Sealing (0-50), HMA Overlay (< 1 in.)
4-7	0-50	170-220	0.5-1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
4-7	0-50	170-220	> 1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
4-7	50-100	0-94	0-0.5	Crack Sealing (50-100), Chip Seal Coat (Polymer Modified Asphalt)
4-7	50-100	0-94	0.5-1	Crack Sealing (50-100), Microsurfacing (Ruts Only)
4-7	50-100	0-94	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (< 1 in.)
4-7	50-100	95-170	0-0.5	Surface Recycling (1 in.), HMA Overlay (< 1 in.)
4-7	50-100	95-170	0.5-1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (< 1 in.)
4-7	50-100	95-170	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (2 in.)
4-7	50-100	170-220	0-0.5	Cold Milling (½ - 1 in.), Crack Sealing (50-100), HMA Overlay (1½ in.)

Age Since Last Treatment	Transverse (cracks/mile)	Average IRI* (in/mile)	Average Rutting (in)	Recommended Treatment Strategy
4-7	50-100	170-220	0.5-1	Surface Recycling (2 in.), HMA Overlay (1½ in.)
4-7	50-100	170-220	> 1	Cold in Place Recycling (4 in.), HMA Overlay (2 in.)
4-7	>100	0-94	0-0.5	Crack Sealing (100+), Chip Seal Coat (Polymer Modified Asphalt)
4-7	>100	0-94	0.5-1	Crack Sealing (100+), Microsurfacing
4-7	>100	0-94	> 1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
4-7	>100	95-170	0-0.5	Surface Recycling (1 in.), HMA Overlay (1½ in.)
4-7	>100	95-170	0.5-1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
4-7	>100	95-170	> 1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
4-7	>100	170-220	0-0.5	Surface Recycling (2 in.), HMA Overlay (1½ in.)
4-7	>100	170-220	0.5-1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (4 in.)
4-7	>100	170-220	> 1	Reconstruction-Surface Only
8-10+	0-50	0-94	0-0.5	Crack Sealing (0-50), HMA Overlay (< 1 in.)
8-10+	0-50	0-94	0.5-1	Crack Sealing (0-50), HMA Overlay (1½ in.)
8-10+	0-50	0-94	> 1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
8-10+	0-50	95-170	0-0.5	Surface Recycling (1 in.), HMA Overlay (< 1 in.)
8-10+	0-50	95-170	0.5-1	Surface Recycling (1 in.), HMA Overlay (1½ in.)
8-10+	0-50	95-170	> 1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (2 in.)
8-10+	0-50	170-220	0-0.5	Cold Milling (> 1 in.), Crack Sealing (0-50), HMA Overlay (1½ in.)
8-10+	0-50	170-220	0.5-1	Crack Sealing (0-50), Microsurfacing (Ruts Only), HMA Overlay (2 in.)
8-10+	0-50	170-220	> 1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
8-10+	50-100	0-94	0-0.5	Crack Sealing (50-100), HMA Overlay (< 1 in.)
8-10+	50-100	0-94	0.5-1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (< 1 in.)
8-10+	50-100	0-94	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
8-10+	50-100	95-170	0-0.5	Surface Recycling (1 in.), HMA Overlay (1½ in.)
8-10+	50-100	95-170	0.5-1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
8-10+	50-100	95-170	> 1	Crack Sealing (50-100), Microsurfacing (Ruts Only), HMA Overlay (2 in.)

Age Since Last Treatment	Transverse (cracks/mile)	Average IRI* (in/mile)	Average Rutting (in)	Recommended Treatment Strategy
8-10+	50-100	170-220	0-0.5	Surface Recycling (1 in.), HMA Overlay (1½ in.)
8-10+	50-100	170-220	0.5-1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
8-10+	50-100	170-220	> 1	Cold in Place Recycling (4 in.), HMA Overlay (2 in.)
8-10+	>100	0-94	0-0.5	Crack Sealing (100+), HMA Overlay (< 1 in.)
8-10+	>100	0-94	0.5-1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (1½ in.)
8-10+	>100	0-94	> 1	Cold in Place Recycling (4 in.), HMA Overlay (2 in.)
8-10+	>100	95-170	0-0.5	Surface Recycling (2 in.), HMA Overlay (1½ in.)
8-10+	>100	95-170	0.5-1	Cold in Place Recycling (4 in.), HMA Overlay (1½ in.)
8-10+	>100	95-170	> 1	Cold in Place Recycling (4 in.), HMA Overlay (2 in.)
8-10+	>100	170-220	0-0.5	Surface Recycling (2 in.), HMA Overlay (2 in.)
8-10+	>100	170-220	0.5-1	Crack Sealing (100+), Microsurfacing (Ruts Only), HMA Overlay (4 in.)
8-10+	>100	170-220	> 1	Reconstruction-Surface Only

* For AADT > 5000, the IRI threshold value is decreased from 170 in./mile to 150 in./mile, while everything else remains the same.

Step 5 Establish MR&R Costs

Table 5.11 summarizes the average costs per mile for typical MR&R treatment types used by the Kansas DOT. This cost information was obtained from recently completed MR&R projects in Kansas. Cost data were reviewed and adjusted for inflation as described in Section 5.2 (step 2).

Table 5.11 Kansas DOT Maintenance Cost Table

Pavement Treatment	Cost per Lane Mile (2009 estimates)	Maintenance Level
Chip Seal Coat	$8,500	Non-Structural
Chip Seal Coat (Polymer Modified Asphalt)	$12,000	Non-Structural
Crack Filling	$3,000	Non-Structural
Crack Sealing (0-50)	$4,000	Non-Structural
Crack Sealing (100+)	$6,000	Non-Structural
Crack Sealing (50-100)	$5,000	Non-Structural
HMA Overlay (< 1 inch)	$40,000	Non-Structural
Microsurfacing	$32,000	Non-Structural
Microsurfacing (Ruts Only)	$25,000	Non-Structural

Pavement Treatment	Cost per Lane Mile (2009 estimates)	Maintenance Level
Slurry Sealing	$32,000	Non-Structural
Cold Milling (> 1 inch)	$6,000	Light
Cold Milling (½ - 1 inch)	$4,500	Light
HMA Overlay (1½ inch)	$50,000	Light
HMA Overlay (2 inch)	$62,000	Light
HMA Overlay (3 inch)	$72,000	Light
Surface Recycling (1 inch)	$25,000	Light
Surface Recycling (2 inch)	$37,000	Light
Cold in Place Recycling (4 inch)	$110,000	Heavy
HMA Overlay (4 inch)	$82,000	Heavy
HMA Overlay (6 inch)	$102,000	Heavy
HMA Overlay (8+ inch)	$122,000	Heavy
Original	$290,000	Original
Reconstruction-Surface Only	$290,000	Reconstruction

Step 6 Estimate Cost of Delayed Maintenance

For this methodology, the consequence of delayed maintenance is assessed in terms of costs. Delayed maintenance costs are simply the cost difference between typical agency MR&R schedule (baseline) and MR&R performed after a given deferral period (1 to 5 years). The consequences of delayed maintenance are evaluated at the pavement segment level and then aggregated at the corridor or network level.

For this pilot case study, typical Kansas DOT practice was followed to create a baseline MR&R scenario (beginning in the current year, 2011). MR&R needs and associated costs were identified over the 15-year analysis period based on the predicted pavement conditions in the years at which at least one of the performance metrics reached the analyst-defined threshold values. The costs recurring over the analysis period were discounted to current year costs by applying appropriate "real" discount factors reported in OMB Circular A-94, Appendix C.[55]

For the pilot analysis, the consequences of delayed maintenance were simulated by deferring the MR&R schedule for up to 5 years in 1-year increments and determining the effects of the delay on MR&R needs and costs. The steps used in analysis are detailed below.

[55] http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Step 6.1 Select the baseline scenario.

The first step in this process is to select the baseline scenario for the pilot case study. The baseline scenario was adapted after typical Kansas DOT MR&R practices. Kansas's typical practice is to select an appropriate MR&R treatment strategy by comparing the actual or forecasted pavement conditions, as characterized by transverse cracking, rutting, and IRI, against the thresholds set in the decision matrix (refer to Table 5.10 above. Assuming that there are no funding constraints, the DOT normally would undertake MR&R actions in the current year with no delay.

Step 6.2 Select a deferral period.

In this case study, it is assumed that the agency typically would delay the scheduled maintenance no more than 5 years. Assuming that the current year is 2011, this case study evaluated the consequences of MR&R delay deferred up to 2016 in 1-year increments.

Step 6.3 Select analysis period.

An analysis period of 15 years is deemed reasonable to capture the differences in the effectiveness of immediate and subsequent MR&R treatments. The MR&R needs and associated costs were identified over a period of 15 years for both the baseline and delay maintenance scenarios.

Step 6.4 Estimate baseline MR&R needs and associated costs.

For the baseline scenario, MR&R actions in 2011 through 2026 and associated costs were identified for each roadway segment as follows:

- Pavement conditions (transverse cracking, rutting, and IRI) were projected through 2026.
- The predicted conditions were compared with Kansas DOT thresholds that trigger MR&R action and the intervention year was identified. The intervention year is the year at which at least one of the predicted performance metrics is expected to reach the acceptable thresholds and trigger the need for MR&R action.
- Appropriate MR&R action were selected as needed based on Kansas DOT's MR&R decision matrix (Table 5.10).
- The pavement condition was reset after every MR&R intervention.
- The process was repeated as needed over the analysis period.
- An MR&R strategy was established over the analysis period (i.e., the sequence of specific MR&R actions and corresponding intervention timing).
- MR&R strategy costs streams were established (i.e., costs associated with each MR&R action were developed using the unit cost values presented in

Table 5.11. The estimated costs were then converted to 2011 dollars by applying appropriate discount factors.

An example is presented here to illustrate the approach used at both the segment and corridor level to determine intervention timing, MR&R needs, and associated costs. For this example, a roadway segment (PMS ID: 0321070018191) on I-70 westbound between mileposts 93.912 and 94.897 was selected. This portion of I-70 originally was constructed in 1962 as an FDAC pavement. Since 1962, the section has undergone several MR&R interventions. The last MR&R intervention was a non-structural maintenance treatment applied in 1998.

Future pavement condition was projected using the global pavement performance models. Table 5.12 presents the projected performance of all three metrics from the last intervention year (1998). The table indicates that the predicted number of cracks per mile exceeded the allowable threshold in 2009 (table cells shaded in grey). Using Kansas DOT's MR&R decision matrix presented in Figure 5.11**Error! Reference source not found.**, appropriate MR&R treatments were selected (crack sealing for 100+ feet and HMA overlay less than 1 in).

Table 5.12 Projected performance in 2011 for PMS ID: 0321070018191

Year	IRI (in./mile)	Transverse Cracking (cracks/mile)	Rutting (in.)
1999	44	17	0.08
2000	53	32	0.12
2001	60	46	0.15
2002	65	59	0.18
2003	70	78	0.22
2004	74	92	0.24
2005	78	106	0.27
2006	81	120	0.29
2007	84	134	0.31
2008	86	148	0.33
2009	89	161	0.35
2010	91	175	0.37
2011	93	188	0.39
Thresholds	**150**	**150**	**0.50**

The pavement condition for this segment was reset to reflect the application of MR&R treatments. The future condition was again projected to identify the

subsequent intervention timings and treatments. The performance projections indicated the need for a similar non-structural intervention in 2020. No further interventions were required. The deterioration of pavement condition and the sequence of MR&R actions with their associated costs are presented in Figures 5.14 through 5.16.

Figure 5.14 Progression of transverse cracking for baseline scenario (PMS ID: 0321070018191)

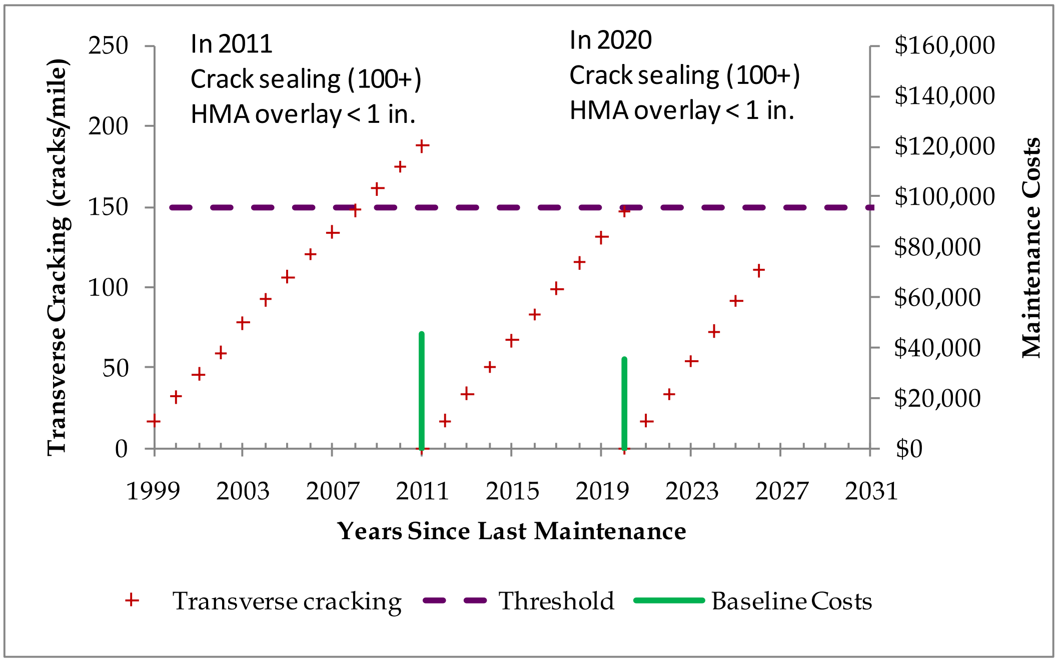


Figure 5.15 Progression of rutting for baseline scenario (PMS ID: 0321070018191).

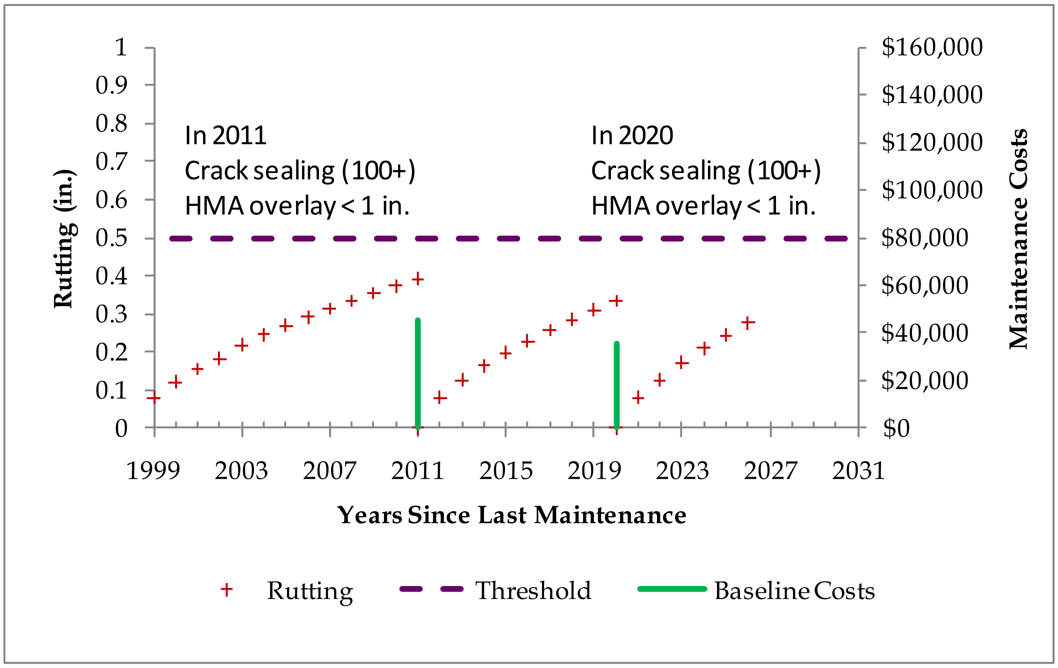
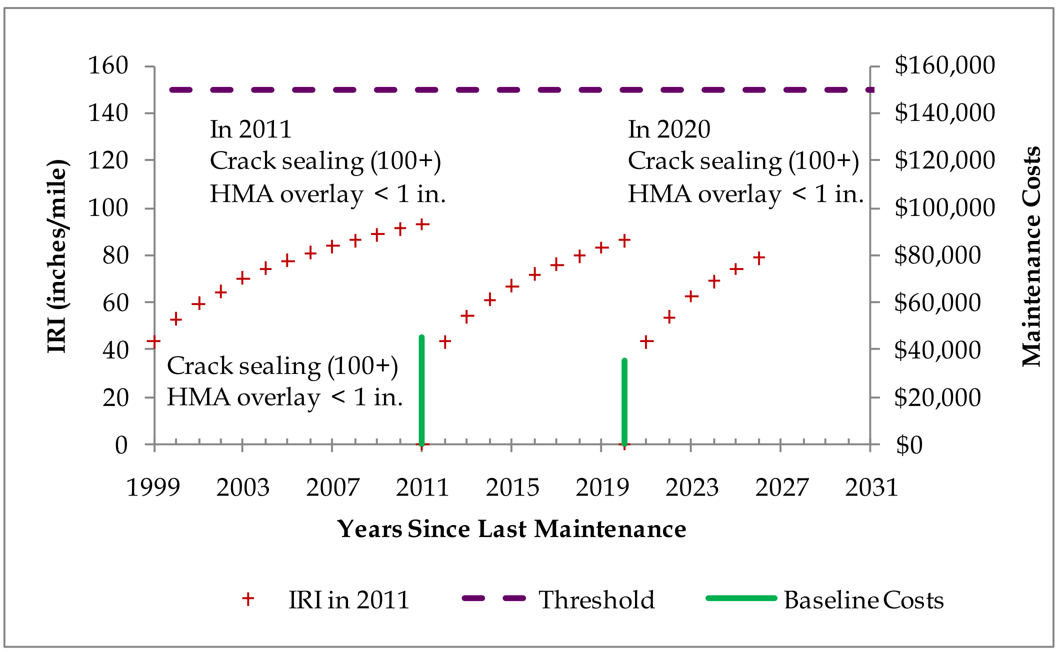


Figure 5.16 Progression of smoothness for baseline scenario (PMS ID: 0321070018191)



These steps were repeated for each roadway segment on I-70 & US 400. The overall discounted costs were then aggregated at the corridor level. The aggregated costs were summarized by each year to present an outlay of annual maintenance expenditure over the analysis period.

Figure 5.17 presents the corridor-wide MR&R strategy for the baseline scenario. The figure indicates that approximately half of the segments on the subject corridors need non-structural intervention, while the other half need light maintenance actions.

Figure 5.17 Corridor-wide MR&R needs for the MR&R baseline scenario

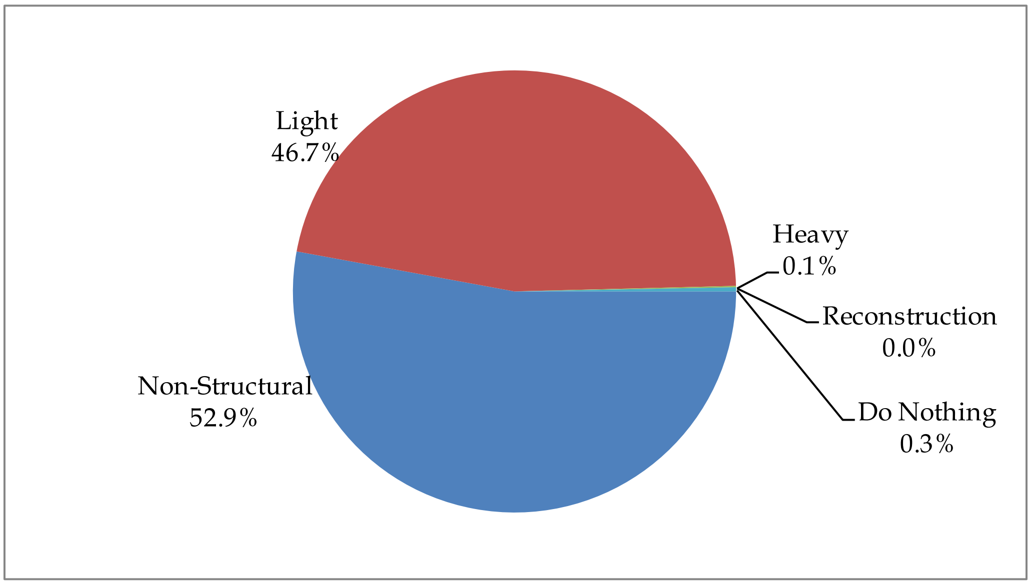
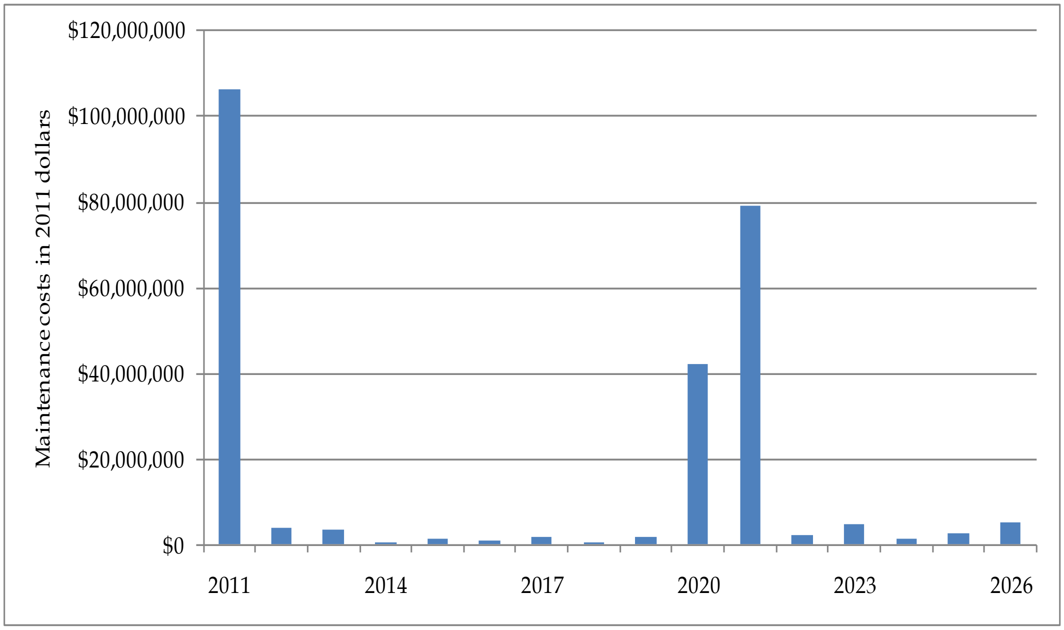


Figure 5.18 presents the expected annual maintenance expenditure outlay for the next 15 years for the baseline scenario.

Figure 5.18 Corridor-wide maintenance costs outlay for the MR&R baseline scenario (in 2011 dollars).



Step 6.5 Estimate MR&R needs and associated costs for delayed maintenance.

This step involved reviewing several "what if "scenarios for evaluating the MR&R needs if the MR&R intervention is delayed by up to 5 years (in 1-year increments). Delayed MR&R strategies were determined using the same approach outlined in step 4. Note that the delayed strategies were more aggressive than the baseline.

Figure 5.19**Error! Reference source not found.** presents the corridor-wide MR&R strategy for the 5-year MR&R delay scenario. The figure indicates a significant decrease in non-structural MR&R needs and corresponding increase in light and heavy MR&R needs for the roadway segments in the I-70 & US 400 corridors. This trend is as expected, as an extended delay in MR&R applications results in significantly more deteriorated pavements and requires more aggressive MR&R treatments. **Error! Reference source not found.**

Figure 5.19 Corridor-wide MR&R needs for the 5-year MR&R delay scenario

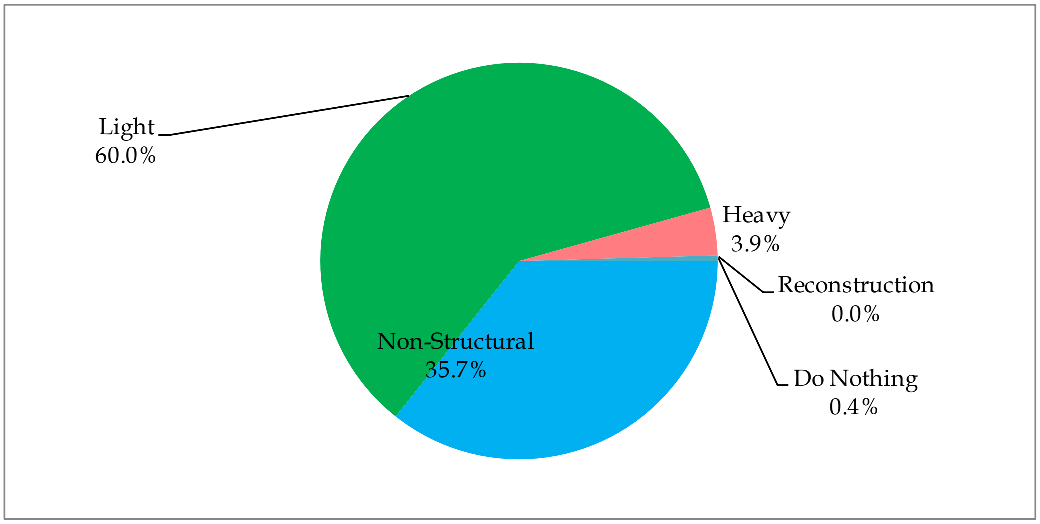
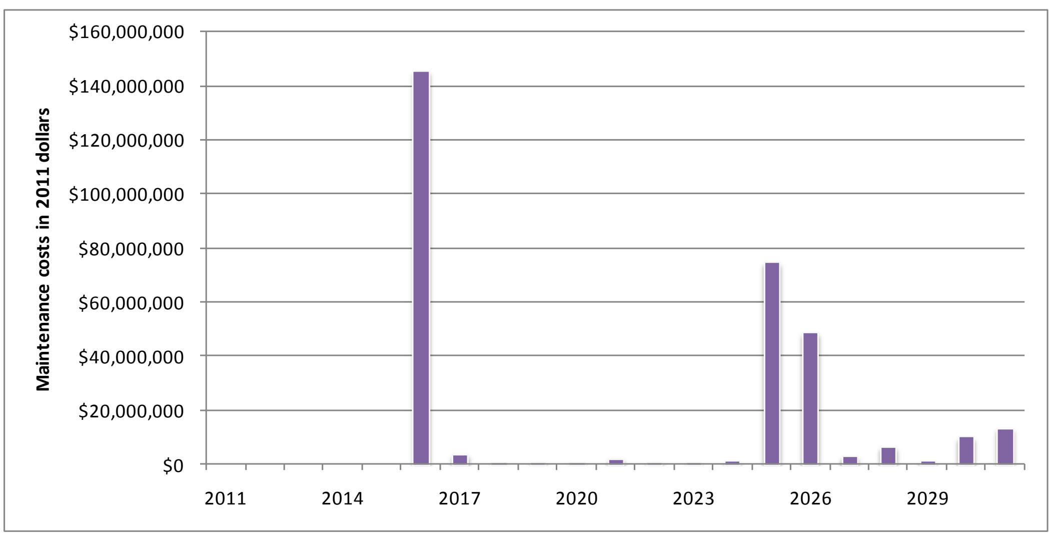


Figure 5.20 presents the expected annual maintenance expenditure outlay for the 15-year analysis period for the 5-year MR&R delay scenario. Compared to the baseline MR&R expenditure outlay, the 5-year MR&R delay scenario requires significantly greater expenditures.

Figure 5.20 Corridor-wide maintenance costs outlay for the 5-year MR&R delay scenario (in 2011 dollars).



Step 6.6 Evaluate the Consequence of Delayed Maintenance

The expenditure outlays for MR&R needs over the analysis period were compared for both baseline and 1- to 5-year delayed MR&R scenarios by discounting them to 2011 dollars. Figures 5.21 and 5.22 present the consequences of delayed maintenance in terms of percent increase and absolute difference in

MR&R costs when compared to the baseline scenario, respectively. The findings illustrate that:

- As expected, delaying maintenance increases costs;
- The cost increase becomes significant after a 3-year delay; and
- There is 2- to 3-year window in which maintenance can be delayed without significant cost implications.

Figure 5.21 Percent increase in the MR&R costs (in 2011 dollars).

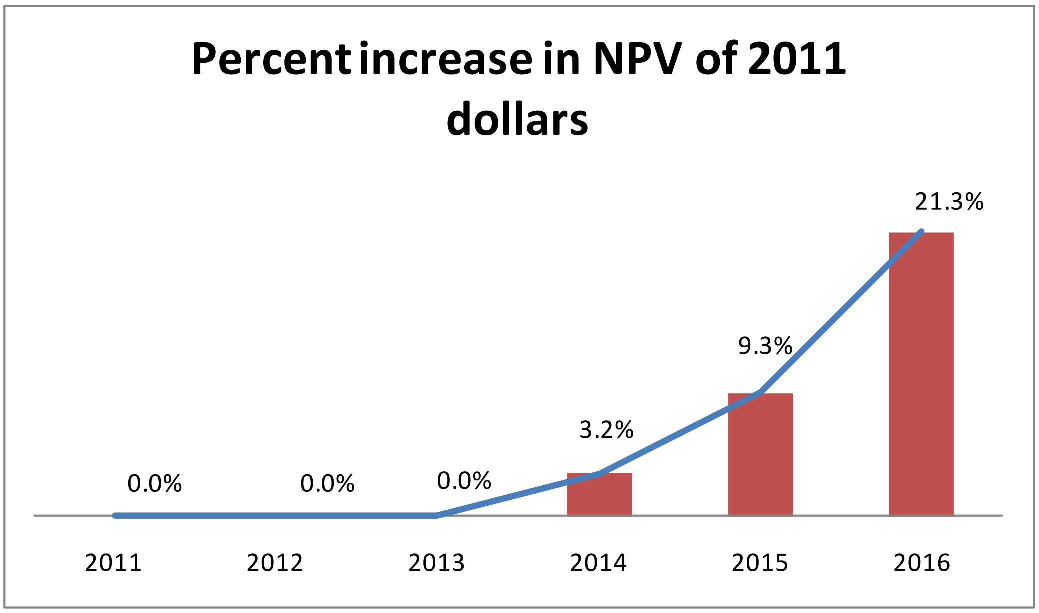
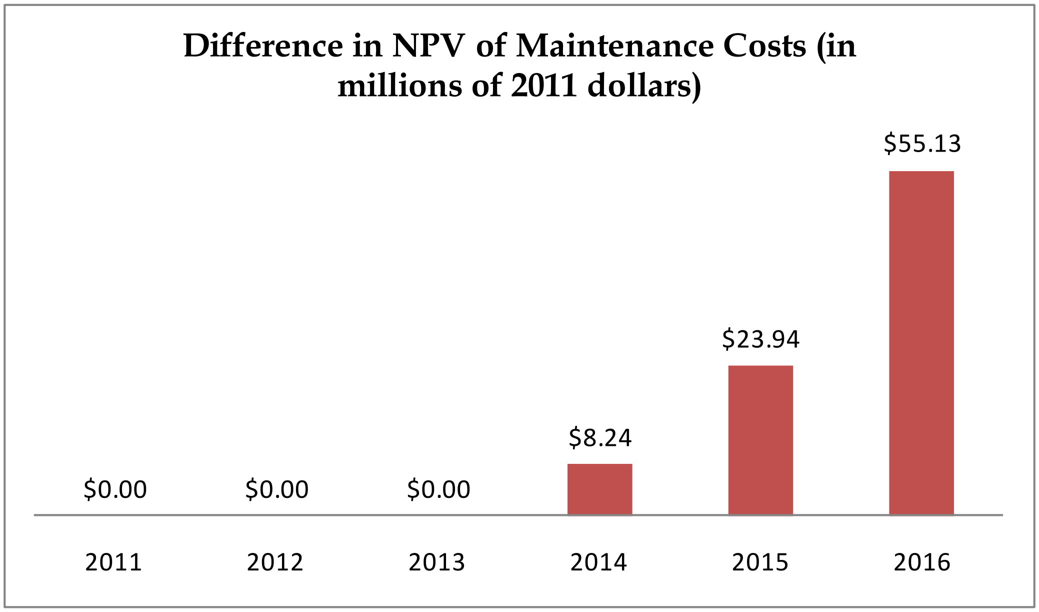


Figure 5.22 Difference in MR&R costs (in millions of 2011 dollars).



The segment level and corridor-wide examples presented above show the proposed methodology for estimating the consequences of delayed maintenance is reasonable and can be used by practicing maintenance engineers. The methodology can consider a wide variety of pavement conditions characterized using different performance metrics, a wide range of M&R treatment actions and strategies, segment level and corridor/network-wide applications, and several delayed maintenance scenarios.

6.0 Phase II Work Plan

This section presents a work plan for Phase II. Phase II includes development of analysis methods for other (non-pavement and non-bridge) highway assets. This work plan reflects the findings and lessons learned from Phase I of the research.

6.1 WORK TASKS

Task 7. Extend the Phase I Bridge Model for Culverts

Objective

Modify the bridge methodology and tool developed in Phase I for large culverts.

Work Steps

The work performed in this task will address how to quantify consequences of delayed maintenance for culverts, using the methodology and prototype tool developed for bridges in Phase I. It is anticipated that the modeling approach and the calculation of agency cost calculations will follow closely the methodology for bridges. However, since culverts are typically represented as a single element, estimating user costs may require inferring the existence of a deck, or adding the user cost terms from the deck model to the culvert element.

Once the methodology is developed, the research team will update the prototype bridge tool from Phase I, and apply it for a number of delayed maintenance scenarios using National Bridge Inventory (NBI) data from the same four states analyzed in Phase I.

Deliverable

- Technical memorandum documenting the culvert analysis methodology.
- Updated bridge prototype tool (in spreadsheet form) that can be used to analyze culverts.
- Documentation on using the tool, to be incorporated into Interim Report #2, as part of Task 9.
- Results of the analysis, to be incorporated into Interim Report #2, as part of Task 9.

Task 8. Develop the Traffic and Safety Asset Model

Objectives

Develop a process for quantifying the consequences of delayed maintenance for traffic and safety assets, and demonstrate the process for selected assets and scenarios.

Work Steps

The work performed in this task will address how to quantify the consequences of delayed maintenance for traffic and safety assets, the major class of assets for which delayed maintenance is a concern besides pavement and bridge assets. Traffic and safety assets include signs, signals, lighting, pavement markers/markings, guardrails, and other features designed to enhance mobility and improve safety.

Traffic and safety assets are important in that they enhance mobility and safety, and agencies have significant investments in them. However, in contrast to the situation for roads and bridges, agencies typically have relatively sparse data for these assets. Also, the relationship between the conditions of these assets and overall system performance is not as well established as it is for pavements and bridges. This task will quantify models for three common types of traffic and safety assets, detail an example of the calculation of consequences of delayed maintenance using data from one agency, and discuss how to extend the models to additional asset types.

As detailed in the review performed in Phase I, there are a number of potential consequences of delaying needed maintenance. In the context of traffic and safety asset, these include but are not limited to:

- **Change in agency costs:** If an asset is not maintained, then an agency may incur additional costs to address the needed maintenance, either because a more aggressive treatment is needed as a result of the deferral, or because the asset may fail during the deferral period, forcing emergency repairs. For instance, an agency may find it must replace fallen regulatory signs that were overdue for replacement, spending more on a per-sign basis to perform piecemeal replacements rather it would have spent to replace all of the signs along a corridor. On the other hand, delaying maintenance reduces agency costs in the short term, and may result in net savings for some assets.

- **Reduced safety:** Certain assets are specifically intended to improve safety. Though the relationship between the performance of a single asset and overall safety performance is difficult to establish, the relationship is no less real as a result of this difficulty. All things being equal, it can be assumed that safety would be degraded if an agency was forced to allow lamps to burn out, markings and signs to fade, and guardrails and traffic barriers to fall into disrepair.

- **Reduced mobility:** In the case of signals and some other traffic and safety assets a consequence of delaying maintenance may be reduced mobility. For instance, if delaying maintenance has the consequence of increasing the probability that a signal will fail, this translates into an increased probability that the signalized intersection will be forced to be behave as an unsignalized intersection during the failure interval,
- **Reduced energy costs:** A positive impact of delaying maintenance can be to reduce energy consumption of traffic safety assets, to the extent that deferring maintenance may result in these assets being disabled or otherwise removed from service. For instance, a number of localities have recently explored "turning off the lights" to reduce cost of maintaining street lights and reduce energy consumption.

Determining the effects of delayed maintenance for traffic and safety assets will involve developing performance models that predict how asset performance will be impacted by delayed maintenance, as well as models for relating reduced performance to other agency and user impacts. This work will be performed in the following steps:

- **Finalize assets for detailed modeling.** The approach developed in this task will be applicable to all traffic and safety assets. However, the approach will focus on demonstrating approaches on three assets (in addition to culverts, which will be addressed in the prior task). Based on the results of the review concerning available data and models, it is anticipated that models can be developed for three assets that demonstrate the full set of impacts outlined above: signs, pavement markers and lighting.
- **Develop performance models.** The next step of the task will be to develop models for relating maintenance to performance. The research team will model performance using Weibull distributions that predict the probability of asset failure based on age and other variables (e.g., extent of maintenance). The Phase I review showed that agencies typically have little data for these assets, suggesting that data would not likely be available to support a condition-based approach, such as that described for pavements and bridges.
- **Develop consequence models.** The next step in this task will be to develop models relating delayed maintenance to agency and user costs, considering probability of asset failure, increased agency costs, and user costs of accidents and delay. This work will leverage models developed previously and surveyed in the Phase I review. For example, FHWA's crash reduction factors will be used to the extent possible for characterizing potential safety impacts of delayed maintenance.
- **Obtain data.** Next the research team will develop a prioritized list of agencies to contact to obtain representative data for use in model calibration. Several agencies, most notably Washington State DOT and Oregon DOT, have developed inventories of traffic and safety assets and are ideal

candidates, assuming the agency is willing to participate in the study. The list candidate agencies and rationale for selection will be submitted to NCHRP for review, comment, and approval. Agency contact will be initiated upon approval.

- **Perform Analysis.** Next, the research team will define a set of deferred maintenance scenarios. It is anticipated that these scenarios will, at a minimum be based on the duration of maintenance delay (as done in Phase I for the bridge and pavement analysis). Once the scenarios have been defined, the research team will apply the performance and consequence models to predict the consequences of delayed maintenance using the data sets obtained previously.
- **Demonstrate Analysis in a Prototype Tool.** The research team will develop a spreadsheet tool that can be used to automate the analysis approach. A description of the prototype tool and the results of the analysis will be incorporated directly into final report prepared as part Task 8.

Deliverables

- Technical memorandum documenting the analysis methodology for signs, pavement markers, and lighting.
- Prototype tool (in spreadsheet form) that can be used to perform the analysis.
- Instructions for using the tool, to be incorporated into Interim Report #2, as part of Task 9.
- Results of the analysis, to be incorporated into Interim Report #2, as part of Task 9.

Task 9. Prepare Interim Report #2

Objective

Document the results of Tasks 8 and 9.

Work Steps

In Tasks 9, the research team will incorporate the results from Tasks 7 and 8 into Interim Report #2. The report will describe the methodologies developed for culverts and traffic and safety assets, present the results of the pilot application of these methodologies, and describe the prototype tools developed to automate the methodologies.

The report will be submitted to NCHRP. All feedback received will be incorporated directly into the final documentation as part of Task 10.

Deliverable

- Interim Report #2 - Electronic version and 12 hard copies.

Task 10. Prepare Final Documentation

Objective

Prepare a final report documenting the entire research effort, and a standalone manual documenting the process for quantifying the consequences of delayed maintenance.

Work Steps

This task includes the development of two interrelated documents: 1) a final report documenting the entire research effort; and 2) a stand-alone manual that describes the processes for quantifying consequences delayed application of maintenance treatments, and presents example applications of the methodologies. While the two documents will be consistent, the manual will be more streamlined and designed for practitioners wishing to focus on the application of the new analysis methodologies. Both documents will draw from and combine materials from the Phase I and Phase II interim reports, and cover the entire range of assets evaluated during this research effort.

As discussed previously, this research effort will also result in a series of prototype tools. These tools are intended only to present the results of the models developed using the process, and it will be possible to step through the recommended process using the details provided in the guidance manual without use of the prototypes or any commercial software. Nonetheless, pending review by NCHRP, the research team would recommend offering the prototypes in CD form to accompany the final report of the project. Therefore, the final report will include instructions for using the prototypes.

In preparing the final documentation, the research team will first prepare annotated outlines for both documents and submit to NCHRP for review. The research team will then develop the materials.

Deliverables

- Outline of the project report and guidance manual.
- Final project report – Electronic version and 12 hard copies.
- Guidance manual – Electronic version and 12 hard copies.

6.2 PHASE II SCHEDULE

Figure 6.1 presents a schedule for Phase II. It assumes that work on Phase II will begin in January 2012. Assuming that start date, all work will be completed by May 2013, the original end date for this research effort.

Figure 6.1 Phase II Progress Schedule

RESEARCH TASK	2011				2012												2013				
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
7. Extend Bridge Model																					
for Culverts					15	30	45	60	75	100											
8. Develop Traffic and Safety																					
Asset Model					15	30	45	60	75	100											
9. Prepare Interim Report #2																					
										15	30	45	60	75	90	90	90	100			
10. Prepare Final																					
Documentation																	15	30	45	75	100