Preliminary Investigation (PI-0244)

Caltrans Division of Research, Innovation and System Information

Quantifying the Benefits of Routine and Preventive Maintenance: Survey of Practice

Requested by
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April 23, 2020

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Executive Summary

Background

California Department of Transportation (Caltrans) field crews perform a wide range of routine and preventive maintenance activities on highway infrastructure and assets. The impact of these activities on asset performance—improvements in asset conditions, reductions in deterioration rates and contributions to asset life cycle or performance—has not been quantified or adequately documented.

Caltrans is seeking information about methodologies used by other state departments of transportation (DOTs) and by the freight, trucking and rail industries to quantify the benefits of routine and preventive maintenance. Caltrans will use this information to develop a methodology that quantifies the impacts of these maintenance activities and relates the impacts to asset performance.

To assist Caltrans in this information-gathering effort, CTC & Associates surveyed state DOTs and other transportation-focused agencies about the methodologies used by these agencies and their experience quantifying the benefits of maintenance on asset performance. A literature search was also conducted to identify publicly available sources of best practices.

Summary of Findings

Survey of Practice

An online survey examined methods and practices used by transportation agencies to quantify the savings and prolong the life of the following assets:

- Pavement.
- Bridges.
- Culverts.
- Intelligent transportation systems (ITS).
- Other assets pertaining to a transportation-related industry.

The survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Performance-Based Management and to representatives from freight, trucking and rail industries. Sixteen representatives from nine state DOTs responded to the survey. None of the freight, trucking and rail industry representatives responded.

Survey results from the state transportation agencies are summarized below in the following topic areas:

- Current quantification programs.
- Program implementation in progress.
- Plans for program implementation.
- No quantification program.

Current Quantification Programs

Five respondents representing state DOT asset management and maintenance functions reported on a program to track routine and preventive maintenance activities and quantify their impact on asset condition:

- Asset Management: Kansas, Minnesota and North Dakota DOTs.
- Maintenance: Tennessee and Utah DOTs.

The Minnesota DOT respondent noted that because the unit has only recently developed its expenditure and activity tracking systems, assessing the effectiveness of some treatments is anecdotal because of the limited number of sample sizes.

Cost Savings

Three respondents—Minnesota, North Dakota and Tennessee DOTs—use modeling practices and cost comparisons to determine the cost savings resulting from maintenance activities. Minnesota DOT uses deterministic modeling, and in North Dakota, a pavement management model maximizes the area under a cost–benefit curve for investments. Costs of various preventive maintenance treatments in Tennessee are compared with typical treatments along with the number of years that are added to the life cycle. The Kansas DOT respondent was unable to provide cost information, and the Utah DOT respondent reported that to date, no cost savings have been identified for culverts.

Investment Reductions

Among the methods used to determine investment reductions for major capital improvements are engineering judgment (Kansas) and a trade-off analysis that determines how best to optimize available funding to best preserve assets (Tennessee). In Minnesota, other needs are balanced against asset management needs when preparing 10-year plan investment directions. Performance is also considered in Minnesota, but the decisions are subjective. Major capital investments have not caused preventive maintenance reductions in North Dakota in recent years. In Utah, no investment reductions on culverts have been made.

Asset Deterioration

Pavement condition data is commonly used by Kansas, North Dakota and Tennessee DOTs to determine if asset deterioration has slowed. The Tennessee DOT respondent noted that pavement condition data is collected annually on all National Highway System (NHS) routes and every two years on non-NHS routes, allowing the unit to track historical deterioration and forecast pavement deterioration. Utah DOT is currently determining life cycle costs for culverts along with their associated deterioration rates based on locations throughout the state.

Evaluation Tools and Methods

Proprietary modeling systems used to quantify the impact of maintenance activities include AASHTOWare Bridge Management (BrM) (Kansas) and Deighton Total Infrastructure Management System (dTIMS) (North Dakota). In Tennessee, a pavement management system, bridge management system and maintenance management system track budget, work performed, asset condition and expenditures. Utah DOT anticipates that its new asset/maintenance management system will collect real-time data and display changes to asset conditions as treatments are applied. The respondent from Minnesota DOT Asset Management reported that the unit uses pavement decision trees and scenarios.

New Tracking/Quantification Activities

Four new tracking and quantification activities are being considered to assess the impact of maintenance activities on asset performance: accrual of historical data (Minnesota), assumption sensitivity analysis (Minnesota), acquisition of a maintenance management system (North Dakota) and revised maintenance activity standards (Utah, which is currently rewriting its standards to be asset-based).

Program Successes

Successes described by respondents include enhanced decision-making (Kansas), stakeholder trust in agency investment strategies (North Dakota) and funding to further inventory and condition data (Utah). The Minnesota DOT respondent reported on the value of software programs and processes that provide cost information and allow return on investment computations. Utah DOT's program has provided a framework for gathering condition data statewide.

Program Challenges

Challenges experienced when quantifying the benefits of routine and preventive maintenance include insufficient resources (Minnesota and North Dakota) and ineffective modeling (North Dakota). The Kansas DOT respondent noted that using surface data does not always give a complete assessment of pavement condition, and Utah DOT is working to create a complete inventory.

Program Implementation in Progress

Minnesota DOT Office of Bridges has developed and implemented a program that tracks preventive maintenance activities tied to inspection elements, which are then tied to resource and cost data within a software tool. But assessing the impact on asset condition has only begun. The respondent provided details about the unit's efforts to institute a program, which are summarized below:

Cost savings methodology. The unit is currently developing methods that compare the deterioration rates of bridges that have received a high level of maintenance to bridges that have received a lower level of maintenance in conjunction with major preservation schedule and cost information.

Investment reductions for major capital improvements. Several years ago, the agency showed potential bridge preventive maintenance payback based on an assumption of increased deterioration and additional maintenance needed when preventive maintenance was not performed. The high-level analysis was based on older data and used engineering assumptions, and the agency currently plans to validate the findings with actual deterioration data.

Impact on asset deterioration. Minnesota DOT is participating in a pooled fund program study that is developing a select number of deterioration curves to provide the needed utility for the time-dependent deterioration of bridge elements. Data will be used to estimate future conditions and work actions.

Tools/methods. Tools and methods used to quantify the impact of maintenance activities on agency assets include surveys of district staff that assess effectiveness and visual inspections of areas that do not receive preventive maintenance.

Program successes. Tracking software was successfully implemented. Maintenance activities are also correlated with timesheet data to calculate activity costs per square foot of bridge deck; quantifying these benefits has been more challenging.

Program challenges. Program challenges are difficulty isolating maintenance activities to determine more cost-effective strategies, reduction or elimination of additional variables that can affect deterioration, ineffective modeling and inconsistent maintenance practices.

Plans for Program Implementation

Seven respondents from four state DOTs—Colorado, Illinois, Utah and Washington—reported that their functional units are planning to institute a program that translates the quantifiable impacts of maintenance activities on asset condition:

Colorado. Bridge Asset Management has implemented a program to perform deck rehabilitation, joint replacement and other preventive bridge work, and is working with maintenance crews to institute routine bridge cleaning and minor preventive maintenance. The unit is refining its methods to track completed projects and their effects on inventory condition at a more detailed level.

Illinois. Maintenance and Operations is planning a hot-mix asphalt pothole maintenance research study based on a 2017 Minnesota DOT project that developed best practices and guidance for selecting pothole repair materials and methods. The agency would like to evaluate Minnesota DOT's guidance for possible use in Illinois.

Utah:

Bridge Management. The unit has not fully vetted a systematic quantification method but provided details about current practices:

- *Slowing asset deterioration*. Bridge deck deterioration curves are evaluated based on the type of overlay treatment placed and when it was placed (with or near initial construction or later in the life cycle of the bridge).
- *Tools/methods used*: BrM and visual inspections.
- *New practices under consideration*: Better documentation of preservation activities and when they occur.
- *Successes*: Identification and use of deterioration curves for bridge decks.
- *Challenges*: Documentation of the preservation treatments, changes in data collection practices over time, and outside factors other than overlays that affect overall deck condition.

Intelligent Transportation System (ITS). A work order system tracks repairs and maintenance of reported issues with ITS devices, but the system is not used for tracking preventive or routine maintenance of the devices. Also, the unit has begun using WhatsUp Gold, a service that monitors the communications health of the unit's ITS systems. The unit plans to use the findings to quantify the effects of routine maintenance in terms of communications up- and downtime.

Washington. A system that tracks completed work gathers the location of the project and type of maintenance conducted but does not track labor, equipment, materials and other costs. A budget tool includes expenditures and can retrieve labor, equipment, materials and other cost information from a separate program.

Washington State Pavement Management System (WSPMS) tracks annual pavement performance and retrieves information from the agency's maintenance program. While WSPMS shows the impact that pavement maintenance may have on pavement performance, it does not include budget information.

No Quantification Program

Respondents from three state DOTs—Utah (pavement), Washington (stormwater and drainage) and Wyoming (planning)—reported that their functional units do not have a program that quantifies the impacts of maintenance activities on asset condition and do not have plans to institute one. Wyoming DOT examined the history and impacts of routine and preventive maintenance treatments in the state but could not validate the impact on the deterioration curves. The agency determined that "if the treatment did not affect the performance measure, such as ride, rut or cracking, then it was routine."

Related Research and Resources

A literature search of recent publicly available resources was conducted to identify national and state publications and guidance about efforts by state transportation agencies and the freight, trucking and rail industries to quantify the impacts of routine and preventive maintenance activities. This effort included a search of transportation agency practices that quantify the benefits of the highway maintenance activities associated with major capital improvement projects focused on rehabilitation. The literature search uncovered no guidance for quantifying the benefits of routine or preventive maintenance in industries related to transportation. A sampling of national and state transportation agency guidance was identified for multiple asset classes, bridge maintenance and pavement preservation.

Multiple Asset Classes

A National Cooperative Highway Research Program (NCHRP) project in progress anticipates developing a guide for state DOTs and other transportation agencies to incorporate maintenance costs in a risk-based transportation asset management plan. A 2017 NCHRP report includes a discussion of quantifying the consequences of delayed maintenance for several asset groups, including pavements, bridges and culverts. A Kentucky Transportation Cabinet project in progress will review asset and performance management of highway infrastructure. The project will review how other state agencies integrate quality assurance programs into their performance management and/or asset management.

Bridge Maintenance

The benefits of bridge preservation actions are discussed in a 2018 Federal Highway Administration (FHWA) guide, and a 2014 NCHRP project developed a handbook for cataloging bridge element preservation actions, quantifying the benefits of bridge preservation actions, providing decision-making tools to optimize bridge preservation and developing a methodology for determining appropriate preservation funding levels. A 2015 Indiana DOT study identified 10 bridge preventive maintenance activities that will improve the effectiveness of bridge maintenance operations in the state.

Pavement Preservation

Quantifying the effects of preservation treatments on pavement performance are discussed in a 2018 NCHRP report. The guide includes recommended performance measures and a process for assessing the effects of preservation treatments on pavement performance, service life and life cycle cost. A survey of state DOTs about methods used to calculate the benefits of

pavement preservation are reported in a 2011 Indiana DOT report. Other resources addressed the effectiveness of a variety of asphalt pavement maintenance treatments, including crack sealing, and methods for estimating the costs and benefits of preservation activities.

Gaps in Findings

State DOT response to the survey was limited. In addition, none of the representatives contacted from the freight, trucking and rail industries responded to the survey, which limited the perspective of this Preliminary Investigation to state transportation agency experience only. Few practices and program details were received from survey respondents reporting that their functional units had plans to institute a program to quantify the impacts of maintenance activities on asset condition.

Next Steps

Moving forward, Caltrans could consider:

- Engaging with state transportation agency respondents about various systems and processes, specifically:
    - Kansas DOT about its pavement processes, which are not currently available.
    - Utah DOT for its revised maintenance activity standards (expected completion: end of April 2020).
- Following up with respondents from Colorado, Illinois, Minnesota, Utah and Washington State DOTs for updates about their plans to institute a program for quantifying the impacts of routine and preventive maintenance on asset condition.
- Contacting representatives from state DOTs and from the freight, trucking and rail industries who did not participate in the survey for their experience and perspective.
- Reviewing the literature about the effects of preservation actions related to multiple assets, bridge maintenance and pavement maintenance.

Detailed Findings

Background

Maintenance field crews play an integral role in maintaining and operating California's highway infrastructure and assets. California Department of Transportation (Caltrans) field crews perform a wide range of routine and preventive maintenance activities, but the extent to which these activities improve asset conditions, reduce deterioration rates and contribute to asset life cycle or performance has not been quantified or adequately documented. Quantifying the benefits of routine and preventive maintenance in the context of asset management performance, especially in connection with the *California Transportation Asset Management Plan* and the *State Highway System Management Plan*, is of particular interest to Caltrans.

Caltrans is seeking information about methodologies used by other state departments of transportation (DOTs) and by the freight, trucking and rail industries to quantify the impacts of routine and preventive maintenance and relate those impacts to asset performance. This information will be used in the proposed development of a methodology at Caltrans to quantify the impacts of routine and preventive maintenance and relate those impacts to asset performance.

To assist Caltrans in this information-gathering effort, CTC & Associates summarized the results of an online survey of state DOTs and other transportation-focused agencies. The survey examined the methodologies used by these agencies and their experience quantifying the benefits of maintenance on asset performance. A literature search was also conducted to identify publicly available sources of best practices. Findings from these efforts are presented in this Preliminary Investigation in two areas:

- Survey of practice.
- Related research and resources.

Survey of Practice

An online survey was developed that examined methods and practices used by transportation agencies to quantify the savings and prolong the life of assets in the following categories:

- Pavement.
- Bridges.
- Culverts.
- Intelligent transportation systems (ITS).
- Other assets pertaining to a transportation-related industry.

The survey was distributed to state DOT members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Performance-Based Management and to representatives of the following freight, trucking and rail agencies:

- Amerit Fleet Solutions.
- Association of American Railroads.
- Bay Area Air Quality Management District.
- California Association of Port Authorities.
- California Farm Bureau Federation.
- California Ports.

- California Trucking Association.
- Cambridge Systematics.
- Coalition for Clean Air.
- Consolidated Chassis Management.
- Los Angeles County Metropolitan Transportation Authority.
- Natural Resources Defense Council.
- Pacific Merchant Shipping Association.
- Union Pacific.

Survey questions are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Summary of Survey Results

Sixteen representatives from nine state DOTs responded to the survey:

- Colorado (three responses).
- Illinois.
- Kansas.
- Minnesota (two responses).
- North Dakota.
- Tennessee.
- Utah (four responses).
- Washington (two responses).
- Wyoming.

None of the representatives from the freight, trucking and rail industries responded to the survey.

Among these state DOTs, efforts to quantify the savings of maintenance activities varied:

- *Program in place*. Respondents from DOTs in five states—Kansas, Minnesota, North Dakota, Tennessee and Utah—reported on a program that their functional units use to track routine and preventive maintenance activities and quantify their impact on asset condition.
- *Instituting a program*. The Minnesota DOT Office of Bridges has developed and implemented a program that tracks preventive maintenance activities that are tied to inspection elements, but has only begun to try to assess the impact on asset condition.
- *Plans to institute a program*. Seven respondents from transportation agencies in four states—Colorado, Illinois, Utah and Washington—reported that their units do not have such a program, but do have plans to institute one.
- *No program*. Respondents from transportation agencies in three states—Utah, Washington and Wyoming—reported that their units do not have such a program and do not have plans to institute one.

Survey results from the state transportation agencies are summarized below in the following topic areas:

- Current quantification programs.
- Program implementation in progress.
- Plans for program implementation.
- No quantification program.

When available, supplementary resources are provided at the end of each topic area. These resources include guidance and system information provided by respondents or sourced through a limited literature search.

Current Quantification Programs

Five respondents representing state DOT asset management and maintenance functions reported that their functional units have a program to track routine and preventive maintenance activities and quantify their impact on asset condition:

Asset Management

- Kansas.
- Minnesota.
- North Dakota.

Maintenance

- Tennessee.
- Utah.

The Minnesota DOT respondent added that the unit has "fairly recently developed robust expenditure and activity tracking systems. It can anecdotally assess the effectiveness of some of the treatments, but the sample sizes are not large enough to average out variables."

Respondents provided details about their units' quantification practices, which are summarized below in the following categories:

- Cost savings.
- Investment reductions.
- Asset deterioration.
- Evaluation tools and methods.
- New tracking/quantification activities.
- Program successes.
- Program challenges.

Cost Savings

Three respondents—Minnesota, North Dakota and Tennessee DOTs—use modeling practices and cost comparisons to determine the cost savings resulting from maintenance activities. The Kansas DOT respondent was unable to provide cost information, and the Utah DOT respondent reported that to date, no cost savings have been identified for culverts. Table 1 summarizes the practices used by Minnesota, North Dakota and Tennessee DOTs.

Table 1. Methods Used to Determine Cost Savings

Method	State	Description
Cost Comparisons	Tennessee	Costs of various preventive maintenance treatments are compared with typical treatments along with the number of years that are added to the life cycle.

Method	State	Description
Deterministic Modeling	Minnesota	N/R
Pavement Management Model	North Dakota	The model maximizes the area under a cost–benefit curve for investments.

N/R No response.

Investment Reductions

Methods to determine investment reductions for major capital improvements were reported by three respondents: Kansas, Minnesota and Tennessee DOTs. The North Dakota DOT respondent reported that major capital investments did not cause preventive maintenance reductions in recent years. In Utah, no investment reductions on culverts have been made. Table 2 summarizes the practices used by Kansas, Minnesota and Tennessee DOTs.

Table 2. Methods Used to Determine Investment Reductions for Major Capital Improvements

Method	State	Description
Engineering Judgment	Kansas	N/R
Trade-Off Analysis	Tennessee	A trade-off analysis determines how best to optimize available funding to best preserve assets.
Other Considerations	Minnesota	• Other needs are balanced against asset management needs when preparing 10-year plan investment directions. • Performance is considered, but the decisions are subjective.

N/R No response.

Asset Deterioration

Three respondents—Kansas, North Dakota and Tennessee DOTs—described methods to determine if asset deterioration slowed as a result of maintenance activities. Pavement condition data and core samples are commonly used by these respondents to determine if asset deterioration has slowed. Utah DOT is currently determining life cycle costs for culverts along with their associated deterioration rates based on locations throughout the state. Table 3 summarizes the practices used by Kansas, North Dakota and Tennessee DOTs.

Table 3. Methods Used to Determine Reduction in Asset Deterioration as a Result of Maintenance

Method	State	Description
Core Samples	Kansas	N/R

Method	State	Description
Pavement Condition Data	Kansas, North Dakota, Tennessee	*Kansas*. Surface data is used to determine the impact. *North Dakota.* International Roughness Index (IRI) in pavements is graphed annually. *Tennessee*. The unit collects pavement condition data annually on all National Highway System (NHS) routes and every two years on non-NHS routes. By knowing what and when treatments have been applied along with the pavement condition data, the unit is able to track historical deterioration and forecast pavement deterioration.

N/R No response.

Evaluation Tools and Methods

Proprietary bridge, maintenance and pavement modeling systems are used by Kansas, North Dakota, Tennessee and Utah DOTs to quantify the impact of routine and preventive maintenance on agency assets. Minnesota DOT's Asset Management unit uses pavement decision trees and scenarios. Survey responses are summarized in Table 4.

Table 4. Tools and Methods to Quantify Impact on Agency Assets

Method	State	Description
Decision Trees	Minnesota	Pavement decision trees/scenarios.
Proprietary Systems	Kansas, North Dakota, Tennessee, Utah	*Kansas*. AASHTOWare Bridge Management (BrM), a proprietary optimization program (see Supporting Documents). The bridge unit hasn't calibrated all program actions. *North Dakota.* Deighton Total Infrastructure Management System (dTIMS) for pavements (see Supporting Documents). *Tennessee*. A pavement management system (developed by Stantec; see Supporting Documents), a bridge management system and a maintenance management system track budget, work performed, asset condition and expenditures. *Utah*. New asset/maintenance management system is expected to collect real-time data and display changes to asset conditions as treatments are applied.

New Tracking/Quantification Practices

Respondents from Minnesota, North Dakota and Utah DOTs described new tracking and quantification activities that their agencies are considering to assess the impact of routine and preventive maintenance on asset performance:

- Accrual of historical data (Minnesota).
- Assumption sensitivity analysis (Minnesota).
- Acquisition of a maintenance management system (North Dakota).
- Revised maintenance activity standards (Utah). The agency is currently rewriting the standards to be asset-based (condition-focused and able to capture actual unit costs).

Program Successes

Software programs and processes that track maintenance needs, enhanced decision-making and stakeholder trust were among the successes that agencies described when quantifying the benefits of routine and preventive maintenance. Table 5 summarizes survey responses.

Table 5. Successes With Quantifying the Benefits of Maintenance Activities

Success	State	Description
Enhanced Decision-Making	Kansas	Data is fed back to the pavement optimization program. The more data received, the more cost-effective optimization decisions the program prescribes for the "numerous pavement paradigms in Kansas."
Funding	Utah	Obtaining funding has allowed the agency to further its inventory and condition data.
Software/Processes That Track Maintenance Needs	Minnesota	Processes track routine and preventive work for both pavements and bridges. Note: • The unit lacks a robust historical data set that would allow a thorough analysis of actual asset life extension. • Knowing costs allows return on investment computations, given assumptions about life improvements.
Specific Assets	Tennessee	Quantifying the benefits of preventive maintenance in the state resurfacing and statewide bridge repair programs has been particularly successful. Various preventive maintenance measures have extended the life cycle of these assets and reduced maintenance costs.
Stakeholder Trust	North Dakota	Quantifying the benefits of maintenance has allowed the agency to maintain trust with stakeholders about agency investment strategies.
Statewide Approach	Utah	The program has provided a framework for gathering condition data statewide.

Program Challenges

Insufficient resources, ineffective modeling and a narrow framework for evaluating assets were cited as challenges experienced when quantifying the benefits of routine and preventive maintenance. Respondents from four states—Kansas, Minnesota, North Dakota and Utah—described these and other challenges. Responses from these states are summarized in Table 6.

Table 6. Challenges With Quantifying the Benefits of Maintenance Activities

Challenge	State	Description
Narrow Focus	Kansas	Surface data do not always give a complete assessment of pavement condition.

Challenge	State	Description
Incomplete Inventory	Utah	• Creating a complete inventory ("still a work in progress"). • Instituting a decision matrix for culvert systems. A matrix will determine when certain treatments will be made, which will allow the agency to see the benefits of preservation and routine treatments (such as annual cleaning).
Ineffective Modeling	North Dakota	Inability to model the most inexpensive treatment, such as crack sealing.
Insufficient Resources	Minnesota, North Dakota	*Minnesota*: • Insufficient historical data. • Difficulty achieving comparable studies. *North Dakota*. The agency currently does not have a maintenance management system.

Supporting Documents

The resources below present the standard operating guidelines from Tennessee DOT's pavement resurfacing program along with general information about management systems used by Kansas, North Dakota and Tennessee DOTs. Utah DOT is currently revising its maintenance activity standards; they are expected to be completed by the end of April 2020.

Kansas

AASHTOWare Bridge Management, American Association of State Highway and Transportation Officials, December 2019.
https://www.aashtoware.org/products/bridge/bridge-overview/
From the web site: The AASHTOWare Bridge Management software is a comprehensive asset management system developed to assist in the challenging task of bridge management. AASHTOWare Bridge Management stores bridge inventory and inspection data; formulates networkwide preservation and improvement policies for use in evaluating the needs of each bridge in a network; and makes recommendations for what projects to include in an agency's capital plan for deriving the maximum benefit from limited funds.

North Dakota

Deighton Total Infrastructure Management System (dTIMS), Deighton Associates Ltd., undated.
https://www.deighton.com/
Deighton Total Infrastructure Management System (dTIMS) is an infrastructure asset management software program. Its web site includes links to projects in the following sectors:

- Pavements (https://www.deighton.com/roads-highways).
- Bridges (https://www.deighton.com/bridge).
- Stormwater (https://www.deighton.com/water-wastewater).
- Ancillary assets (https://www.deighton.com/ancillary-asset-solutions).

Tennessee

Pavement Resurfacing Program Standard Operating Guidelines, Tennessee Department of Transportation, April 2018.
https://www.tn.gov/content/dam/tn/tdot/maintenance/pavement-office/TDOT-ResurfacingGuidelines-27April2018.pdf
From the introduction:

> The TDOT [Tennessee Department of Transportation] Pavement Management office procures collection of pavement management system (PMS) data to monitor the health of all pavements on the TDOT network. Pavement data collected per this contract can be categorized into two groups—roughness and distress. Roughness data includes factors that define pavement smoothness, such as the international roughness index (IRI) which is used to calculate the Pavement Smoothness Index (PSI). Distress data includes metrics that define the physical deterioration of pavements such as cracking, rutting and other pavement distresses. Pavement data is compiled annually by the Pavement Management office and distributed in an Annual PMS Report.

The guidelines include various tools and practices, including the PMS data collection schedule (page 6 of the report, page 7 of the PDF) and pavement management data metrics (beginning on page 7 of the report, page 8 of the PDF).

Infrastructure Management and Pavement Engineering, Stantec, Inc., undated.
https://www.stantec.com/en/services/pavement-engineering
From the web page:

> Understanding pavement assets within a transportation network—both makeup and condition—is vital for owners of the network. We work with our clients to manage their pavements, focusing on pavement engineering and related data collection services. Our specialists provide pavement testing evaluation, life cycle analysis, design and implementation services for roads, airports, ports and other transportation facilities.

This web page also includes links to national and international efforts in infrastructure management and pavement engineering.

Program Implementation in Progress

The Minnesota DOT Office of Bridges has developed and implemented a program to track preventive maintenance activities that are tied to inspection elements, which are then tied to resource and cost data within an Oracle Business Intelligence tool. But the unit is only beginning to try to assess the impact on asset condition. Details about the unit's efforts to institute a program are summarized below.

Method Used to Determine Cost Savings	The unit is currently developing methods to determine cost savings. Comparisons are underway of the deterioration rates of bridges that have received a high level of maintenance to bridges that have received a lower level of maintenance in conjunction with major preservation schedule and cost information.
Methods Used to Determine Investment Reductions for Major Capital Improvements	According to the respondent, Minnesota DOT developed a document several years ago that showed potential bridge preventive maintenance payback based on an assumption of increased deterioration and additional maintenance needed when

preventive maintenance was not performed. This very high-level analysis was based on older data and used engineering assumptions.

Next step: Validate the findings with actual deterioration data.

Method Used to Determine Impact on Asset Deterioration

Current deterioration curves do not model maintenance work. But Minnesota DOT is participating in a Transportation Pooled Fund program study that is developing a select number of deterioration curves that will provide the needed utility for the time-dependent deterioration of bridge elements to be used in making estimates of future conditions and work actions (see Supporting Documents below). Maintenance data will also be analyzed as part of that study.

Tools/Methods Used to Quantify Impact on Agency Assets

- Surveys of district staff assess current practice with regard to effectiveness of various bridge preventive maintenance activities to assess their impact.
- Visual inspections show the impacts of not performing certain types of preventive maintenance, such as accelerated corrosion on steel beams or accelerated deterioration on substructure elements due to a leaking joint.
- Next step: Compare element condition rating data and maintenance frequency to validate earlier exercises.

New Tracking/ Quantification Activities Under Consideration

The respondent noted that Minnesota DOT defines preservation as a program of cyclical and condition-based maintenance activities that keep bridges in sound condition and slow their deterioration rate. Preventive maintenance, reactive maintenance and major preservation are subcategories of preservation tasks:

- Preventive maintenance (such as flushing, deck sealing, crack sealing, poured joint sealing, barrier sealing, joint repair, and bearing cleaning and lubrication, with the highest priority assigned to crack sealing, joint sealing and flushing). Preventive maintenance includes routine maintenance activities performed on an assigned frequency or an as-needed basis to slow deterioration.
- Reactive maintenance (such as bridge deck spall repair).
- Major preservation (such as bridge overlays).

Minnesota DOT is currently identifying bridges that have had varying levels of maintenance, while trying to minimize the variability of other factors in order to compare deterioration, maintenance schedule and cost as well as major preservation schedule and cost.

Successes With Quantifying Benefits

- The software program that tracks maintenance needs and ties those needs to inspection elements was successfully

implemented. Initially, the unit planned to update element condition as soon as the maintenance task was accomplished, but that proved challenging because of the unit's current inspection report approval process. Data collection allows the unit to track the work backlog and set performance targets.

- Maintenance activities are also correlated with timesheet data to calculate typical activity costs per square foot of bridge deck. Quantifying benefits has been more challenging.

Challenges With Quantifying Benefits

- Difficulty isolating maintenance activities to determine more cost-effective strategies.
- Reduction or elimination of additional variables that can affect deterioration (such as environment, traffic and design type) to determine the real impact of bridge preventive maintenance.
- Ineffective modeling. The National Bridge Inspection Standards (NBIS) program is not designed to help with modeling. As a result, the data has too much scatter and inconsistencies to draw quantitative conclusions.
- Inconsistent maintenance practices.

Supporting Documents

Project in Progress: Bridge Element Deterioration for Midwest States, Transportation Pooled Fund Program, start date: December 2019; expected completion date: December 2021. Project description at https://www.pooledfund.org/Details/Study/655
From the project description: The objective of this pooled fund research is to have multiple Midwest DOTs pool resources and historic Midwest DOT bridge data related to element level deterioration, operation practices, maintenance activities and historic design/construction details. This data will provide the basis for research to determine deterioration curves. A select number of deterioration curves will provide needed utility for the time-dependent deterioration of bridge elements to be used in making estimates of future conditions and work actions. This effort will pool data and through the analysis and research processes create results that will improve accuracy of various bridge management and asset management applications that the member DOTs use (BrM, Agile Assets and other[s]).

Quantifying the Impact of Bridge Maintenance Activities on Deterioration: A Survey of Practice and Related Resources, Minnesota Department of Transportation, 2016. http://www.dot.state.mn.us/research/TRS/2015/TRS1509.pdf
State DOTs were surveyed about their practices to quantify the benefits of various bridge maintenance treatments in relation to remaining service life and bridge life cycle costs. The use and frequency of bridge maintenance treatments were addressed along with quantifying the benefits of bridge maintenance treatments, and the use of bridge deterioration models. Five respondents described the quantification methods used to determine the benefits of bridge maintenance treatments: engineering judgment, condition rating information and funding models compared to performance measure targets.

Deterioration Rates of Minnesota Concrete Bridge Decks, Minnesota Department of Transportation, October 2014.
http://www.dot.state.mn.us/research/TS/2014/201440.pdf
From the abstract: MnDOT [Minnesota DOT] provided decades of inventory and inspection bridge data for this project. This included National Bridge Inventory (NBI) condition code data for 2,601 bridges with concrete decks. Based on conversations with MnDOT, it was agreed that deck deterioration rates would be determined by the length of time bridge decks stay, or drop, at NBI condition codes. We analyzed the data to determine how many years, on average, a bridge deck remains at the various NBI condition code states. We also analyzed the data to determine what factors affect the rate of bridge deck deterioration. We looked at type of deck reinforcement (black bars, epoxy coated top bars and all epoxy coated bars), presence of concrete overlay, average daily traffic (ADT), presence of 3 inches of cover to the top mat of reinforcement, superstructure material and location.

Plans for Program Implementation

Seven respondents from four state DOTs reported that their functional units are planning to institute a program that translates the quantifiable impacts of routine and preventive maintenance on asset condition:

Bridges

- Colorado.
- Utah.

Buildings and Rest Areas

- Colorado.

Intelligent Transportation Systems

- Utah.

Maintenance and Operations

- Illinois.
- Washington.

Pavement

- Colorado.

Utah DOT Bridge Management has begun looking at quantifying the impact of routine and preventive maintenance, but has not fully vetted a systematic quantification method. Information about the unit's current practices is summarized below. Following this summary is supplementary information provided by the other respondents in this category.

Utah DOT: Bridge Maintenance

Method Used to Determine Cost Savings	N/A (Cost savings for bridges have not been identified.)
Method Used to Determine If Maintenance Slowed Asset Deterioration	Evaluation of bridge deck deterioration curves based on the type of overlay treatment placed and when it was placed (with or near initial construction or later in the life cycle of the bridge).

Tools/Methods Used to Quantify the Impact on Agency Assets	• BrM software for data collection. • Visual inspections.
New Tracking/ Quantification Activities Under Consideration	Better documentation of preservation activities and when they occur.
Successes With Quantifying Benefits	Beginning to identify deterioration curves for bridge decks based on the type of overlay placed on a bridge deck and when in the life cycle of the bridge deck the overlay was placed.
Challenges With Quantifying Benefits	• Documentation of the preservation treatments taking place. • Changes in data collection practices over time (from AASHTO Commonly Recognized (CoRe) elements to AASHTO elements). • Outside factors other than overlays that affect the overall deck condition.

N/A Not available.

Supplementary Information From Other Agencies

The other respondents with plans to quantify the benefits of maintenance provided information about their agencies' current practices and programs:

Colorado. Bridge Asset Management has implemented a program to perform deck rehabilitation, joint replacement and other preventive bridge work. It is also working with the agency's maintenance crews to institute routine bridge cleaning and minor preventive maintenance. However, the unit is refining its methods to track completed projects and the effects of those projects on inventory condition at a more detailed level.

Illinois. The respondent noted that the unit is planning a hot-mix asphalt (HMA) pothole maintenance research study similar to a 2017 project conducted by Minnesota DOT that developed best practices guidance for selecting pothole repair materials and methods (see Supporting Documents below). The agency would like to evaluate Minnesota DOT's guidance to develop best practices that apply in Illinois. The respondent added that pavement preservation techniques "are better followed by our research or programming bureaus."

Utah: ITS has implemented the following:

- A work order system tracks repairs and maintenance of reported issues with ITS devices. However, this system is not used for tracking preventive or routine maintenance of the devices.
- The unit has begun using WhatsUp Gold to monitor the communications health of its ITS systems. (WhatsUp Gold is a service that monitors the performance of applications and devices; see Supporting Documents below.) Although a formal practice is not in place, the unit has plans to use the findings to quantify the effects of routine maintenance in terms of communications up- and downtime.

Washington:

- A system tracks work that has been completed. The system includes the location and type of maintenance that was conducted but does not track labor, equipment, materials and other costs.
- Additional programs that are separate from the maintenance program:
    - A budget tool includes expenditures and can collect information from another program that houses labor, equipment, materials and other costs.
    - Washington State Pavement Management System (WSPMS) tracks pavement performance on an annual basis and can retrieve information from the agency's maintenance program (see Supporting Documents below). While WSPMS shows the impact that pavement maintenance may have on pavement performance, it does not include budget information.

Supporting Documents

Illinois

Comprehensive Field Evaluation of Asphalt Patching Methods and Development of Simple Decision Trees and a Best Practices Manual, Jay Dailey, Eshan Dave, Manik Barman and Robert Kostick, Minnesota Department of Transportation, June 2017.
http://www.dot.state.mn.us/research/reports/2017/201725.pdf

(*Note*: Although not provided by the Illinois DOT respondent, this report summarizes the findings from a 2017 project conducted by Minnesota DOT to develop guidance for selecting pothole repair materials and methods.)

From the abstract: The objective of this project was to investigate the effectiveness of different pavement patching methods and to develop simple decision trees and a best practices manual. The performance of 20 different pothole patches, which were patched with four different types of patching methods and located at five different construction sites, were monitored for approximately two years. Based on the observed performance of the pothole patches considered in this study, two forms of decision trees and a best practices manual have been developed for selecting the most appropriate patching method for a given pothole condition. The developed decision trees can be used to select the patching method based on the location of the pothole (e.g., along longitudinal joints, localized potholes, etc.), construction season, condition of the pothole, and pothole area and depth. The best practices manual provides guidelines on the selection of patching method, pothole preparation, placement of patching materials and compaction.

Utah

WhatsUp Gold, Progress Software Corporation, undated.
https://www.whatsupgold.com/
WhatsUp Gold provides "complete visibility into the status and performance of applications, network devices and servers in the cloud or on-premises." The app allows users to monitor application performance, bandwidth consumption, cloud-based resources, network performance, and virtual and wireless networks.

Washington

Washington State Pavement Management System (WSPMS), Washington State Department of Transportation, undated.
https://www.wsdot.wa.gov/engineering-standards/manuals/glossary/washington-state-pavement-management-system-wspms
Key components of the WSPMS are data analysis, WebWSPMS, data collection, distress identification and friction testing. *From the web site*:

> A computer system that stores data about the pavement condition of all the highways in the state. Information available includes the latest field review and past contracts for every main line mile of state highway. Calculations are used to determine whether a given section of pavement is a past due, due or future due preservation need.

Related Resources:

> **Materials Lab—Pavement Management**, Washington State Department of Transportation, undated.
> https://www.wsdot.wa.gov/Business/MaterialsLab/Pavements/PavementManagement.htm
> This web page describes Washington State DOT's long-term involvement in pavement management system implementation and briefly describes WSPMS activities.
>
> **"WSDOT Pavement Management Data—WSPMS,"** WSDOT GeoData Distribution Catalog, Washington State Department of Transportation, undated.
> https://www.wsdot.wa.gov/mapsdata/geodatacatalog/Maps/noscale/DOT_WSPMS/WSPMS_IDX.htm
> Pavement condition data for spatial analysis and mapping can be accessed from this central distribution site of geographic information system (GIS) data.

No Quantification Program

Respondents from three state DOTs—Utah (pavement), Washington (stormwater and drainage) and Wyoming (planning)—reported that their functional units do not have a program that quantifies the impacts of maintenance activities on asset condition and do not have plans to institute one.

The Wyoming DOT respondent added that when the agency examined the history and impacts of routine and preventive maintenance treatments in the state, it could not validate the impact on the deterioration curves. The agency determined that "if the treatment did not affect the performance measure, such as ride, rut or cracking, then it was routine."

Additional Agency Contacts

Survey respondents were asked to recommend other agencies or organizations that have experience with quantifying the impacts of routine and preventive maintenance. The Illinois DOT respondent provided contact information for the following staff members who have experience with preventive maintenance treatments:

Laura Heckel
Programming/Asset Management Engineer
Illinois Department of Transportation
217-785-2791, laura.heckel@illinois.gov

John Senger
Pavement Technology Engineer
Illinois Department of Transportation
john.senger@Illinois.gov

Related Research and Resources

An examination of domestic in-progress and completed research sought information about efforts by state transportation agencies and the freight, trucking and rail industries to quantify the impacts of routine and preventive maintenance activities. This inquiry was supplemented by a review of transportation agency practices that quantify the benefits of the highway maintenance activities associated with major capital improvement projects focused on rehabilitation.

The literature search uncovered no guidance for quantifying the benefits of routine or preventive maintenance in industries related to transportation. The findings presented below, which are focused on transportation agency guidance, represent a sampling of the resources available in three topic areas:

- Multiple asset classes.
- Bridge maintenance.
- Pavement preservation.

Citations may be further organized as national or state guidance, or related research.

Multiple Asset Classes

National Guidance

Project in Progress: NCHRP Project 23-08, A Guide for Incorporating Maintenance Costs Into a Transportation Asset Management Plan, Request for Proposal (RFP), RFP close date: March 5, 2020.
Project description at https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4789
From the objective: The objective of this research is to develop a guide for state DOTs and other transportation agencies on incorporating maintenance costs in a risk-based TAMP [transportation asset management plan], including but not limited to the following:

1. A detailed presentation of procedures for identifying, collecting and managing required data;
2. Using life cycle planning tools and techniques to demonstrate financial requirements and cost-effectiveness of maintenance activities and preservation programs and the potential change in costs and liabilities associated with deferring these actions;
3. Formulating strategies that identify how to invest available funds over the next 10 years (as required by the TAMP) using life cycle and benefit–cost analyses (and other applicable tools and techniques) to measure trade-offs between capital and maintenance activities in alternative investment scenarios; and
4. Designing components of a financial plan showing anticipated revenues and planned investments in capital and maintenance costs for the next 10 years.

NCHRP Research Report 859: Consequences of Delayed Maintenance of Highway Assets, Carlos M. Chang, Soheil Nazarian, Marketa Vavrova, Margot T. Yapp, Linda M. Pierce, William Robert and Roger E. Smith, 2017.
Report available at http://www.trb.org/NCHRP/Blurbs/176740.aspx
From the foreword:

> This report presents a process for quantifying the consequences of delayed maintenance of highway assets that considers the asset preservation policy, the maintenance and budget needs, and the analyses of delayed maintenance scenarios. This process considers delayed maintenance caused by the inability to meet the agency-defined application schedule or the unavailability of the funds required to perform all needed maintenance, and expresses the consequences in terms of asset condition and the costs to owners and road users. Detailed descriptions of the use of the proposed process to quantify the consequences of delayed maintenance for seven highway assets are available online. The information contained in the report will be of immediate interest to state maintenance engineers and others involved in the different aspects of asset maintenance and preservation.

A discussion of quantifying the consequences of delayed maintenance beginning on page 60 of the report (page 69 of the PDF) addresses seven asset groups:

- Pavements.
- Bridges.
- Culverts.
- Guardrails.
- Lighting.
- Pavement markings.
- Signs.

State Research and Guidance

Indiana

Effects of Bridge Surface and Pavement Maintenance Activities on Asset Rating, Tariq Usman Saeed, Yu Qiao, Sikai Chen, Saeed Al Qadhi, Zhibo Zhang, Samuel Labi and Kumares C. Sinha, Indiana Department of Transportation, November 2017.
https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3181&context=jtrp
From the abstract:

> The research product from this project is a set of averages or models that represent the impacts (performance jump, post-treatment performance vs. age relationship and cost) of each treatment type typically applied to INDOT's [Indiana DOT's] assets. The performance impacts are expressed in terms of the requisite performance indicators. The performance jump models showed that the asset's functional class and pre-treatment condition, and the treatment type were major significant predictors of the performance jump and post-treatment performance loss. The first deliverable from this project is the average (mean) impact for each treatment type under investigation. The second is the overall statistical description of the impact, namely, the minimum and maximum impact, and range and standard deviation of impact; [and] a statistical model that predicts the impact as a function of asset and treatment attributes. The third is a set of charts that describe the sensitivity of the treatment impact to factors related to the asset or the treatment. The study also developed cost models for each of the pavement and bridge treatments and used these results to assess the long-term cost-effectiveness of the treatments.

Discussion of the cost-effectiveness of bridge deck surface treatments begins on page 34 of the report (page 42 of the PDF). The authors describe two different measures of cost-effectiveness:

- *Type I*. The change in the asset rating per treatment intensity ($/m^2). For Type I, a treatment that yields a bigger change in asset rating for a given intensity is considered more cost-effective.
- *Type II*. The treatment intensity ($/m^2) that is needed to yield a given change in the asset rating per treatment intensity. For Type II, a treatment for which a smaller intensity is needed to yield a unit change in asset condition is considered more cost-effective. Type II is the reciprocal of Type I.

Similar discussions of Type I and Type II measures of cost-effectiveness also appear in the report:

- Performance jump cost-effectiveness of pavement surface treatments (see page 47 of the report, page 55 of the PDF).
- Service life cost-effectiveness of flexible and rigid surface treatments (see page 48 of the report, page 56 of the PDF).

Kentucky

Project in Progress: Transformation of KYTC Maintenance Rating Program, Kentucky Transportation Cabinet, start date: July 2019; expected completion date: June 2021.
Project description at https://rip.trb.org/View/1638647
From the project description: KYTC's [Kentucky Transportation Cabinet's] Maintenance Rating Program (MRP) uses statistical measures to evaluate the condition of highway infrastructure as well as KYTC's performance. A customer survey determines which assets are measured and how they are weighted in the final score. In response to performance management and asset management receiving heightened scrutiny, this project will review current items on which data are collected as well as scoring targets. These will be compared to asset management and performance management initiatives. Data collection categories that the process would benefit from incorporating and potential adjustments to the scoring process which may accompany changes in data collection will be explored as well. The project will review how other state agencies integrate quality assurance programs into their performance management and/or asset management. Researchers will pay specific attention to condition assessment and inventory collection by asset class to identify asset needs, assist prioritization of maintenance activities, and prepare a business plan for the district and statewide levels.

Bridge Maintenance

National Guidance

Bridge Preservation Guide: Maintaining a Resilient Infrastructure to Preserve Mobility, Federal Highway Administration, Spring 2018.
https://www.fhwa.dot.gov/bridge/preservation/guide/guide.pdf
Establishment of a bridge preservation program is addressed on page 12 of the guide (page 18 of the PDF). Included are discussions of the methods used to evaluate the benefits of bridge preservation actions (page 15 of the guide, page 21 of the PDF) and ways to monitor and measure performance of the preservation program (page 16 of the guide, page 22 of the PDF).

Practical Bridge Preservation Actions and Investment Strategies, NCHRP Project 14-23, David W. Johnston, John M. Hooks, Edward S. Welch, Allen R. Marshall and Jeremy K. Shaffer, November 2014.
http://onlinepubs.trb.org/onlinepubs/nchrp/docs/nchrp14-23_fr-reportsections.pdf
From the executive summary: The objective of this research was to develop a handbook for possible adoption by AASHTO that will (1) assemble a catalog of bridge element preservation actions; (2) quantify the benefits of bridge preservation actions; (3) provide decision-making tools to optimize bridge preservation actions; and (4) develop a method to determine appropriate levels of funding to achieve bridge agency selected goals and performance measures.

Related Resource:

Handbook for Practical Bridge Preservation Actions and Investment Strategies, NCHRP Project 14-23, David W. Johnston, John M. Hooks, Edward S. Welch, Allen R. Marshall and Jeremy K. Shaffer, November 2014.
http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP14-23_FR-HandbookSections.pdf
The introduction includes a description of handbook content:

- Comparison of systems used to describe the major features of a bridge and guide the condition assessment of each, including National Bridge Inventory, AASHTO Commonly Recognized (CoRe) Bridge Elements and AASHTO Bridge Element Inspection Manual.
- Definitions of terms related to preservation of bridge elements including element descriptions, typical defects occurring on each element, typical/feasible preservation actions and service conditions that impact the effectiveness of the preservation actions.
- Catalog of bridge element preservation actions with bridge elements organized by element and typical defects.
- Feasible preservation actions for each type and level of severity/extent of the defect, estimated cost of the preservation actions, and expected extension of element life under varying service conditions.
- Metrics that can be used to analyze the effectiveness of bridge preservation actions, considering when and which action to apply, and the impacts of applying or delaying an action.
- Method to prioritize bridge preservation actions according to the identified metrics. The method provides decision support for selecting among alternate preservation actions for elements, determining the impact on the element, determining costs and compiling those actions for an individual bridge strategy.
- Method to determine appropriate levels of funding to achieve bridge agency selected goals and performance measures at network-level bridge preservation. The method provides decision support for determining the appropriate level of funding over the planning horizon for a group of bridges and assessing the impact of the actions on the group of bridges.
- Software tools (based on Microsoft Excel) to apply the developed methods to assist in quantifying the benefits of selecting appropriate bridge preservation actions and investment strategies.

State Research and Guidance

Indiana

Bridge Preservation Treatments and Best Practices: Final Report, Mark D. Bowman and Luis M. Moran, Indiana Department of Transportation, October 2015.
https://rosap.ntl.bts.gov/view/dot/37609
From the abstract:

> The objective of this research was to review bridge maintenance activities recommended by specialized literature, to examine maintenance activities currently conducted by the various INDOT districts, and also to review maintenance activities performed by several other DOT agencies. Based on the results of this review, a list of 10 new and enhanced bridge preventive maintenance activities was identified to improve the effectiveness of bridge maintenance operations in Indiana. The required conditions and frequency to perform each activity was analyzed, and the cost and benefit of such operations was studied to ensure that the proposed activities are economically feasible and sustainable.

Recommendations begin on page 8 of the report (page 17 of the PDF) and include the 10 preventive maintenance activities researchers recommended that Indiana DOT incorporate in a bridge preventive maintenance program. The report recommends specific actions and the frequency of the maintenance operations for the following maintenance activities:

- Bridge deck cleaning/washing.
- Bridge concrete deck maintenance.
- Bridge joints.
- Bridge bearings.
- Bridge approach slab.
- Superstructure cleaning/washing.
- Spot painting.
- Vegetation control.
- Removing debris from piers/abutments.
- Pin and hanger (or hinge) connection.

Researchers noted that "[t]he recommended preventive maintenance activities are considered to be most effective when performed on an element in good condition. Nevertheless, it is recommended that INDOT perform the bridge preventive maintenance activities for all bridges, but is especially important for new bridges or when a bridge element is replaced by a new one."

Pavement Preservation

National Guidance

NCHRP Research Report 858: Quantifying the Effects of Preservation Treatments on Pavement Performance, Gonzalo R. Rada, James M. Bryce, Beth A. Visintine, R. Gary Hicks and DingXin Cheng, 2018.
Report available at http://www.trb.org/Main/Blurbs/178307.aspx
From the summary, conclusions and recommendations for future research: The use of performance measures that capture the effect of preservation can enhance the state of practice of pavement management. Because performance measures are integral to several decision processes within pavement management (e.g., treatment selection or project prioritization), measures that adequately capture these effects were recommended as part of this research.

The guide includes recommended performance measures and the process for using these measures to assess the effects of preservation treatments on pavement performance, and

hence service life and LCC [life cycle cost]. The guide also provides a step-by-step procedure to identify alternate pavement performance measures in assessing the effects and use of preservation treatments on pavement performance.

State Research and Guidance

Arizona

Evaluation of Maintenance Strategies, Stephen B. Seeds and David G. Peshkin, Arizona Department of Transportation, November 2013.
https://apps.azdot.gov/adotlibrary/publications/Project_reports/pdf/az628.pdf
From the abstract: In the mid-1990s, the Arizona Department of Transportation (ADOT) initiated the Maintenance Cost Effectiveness study (SPR 371) with the development of plans and an experiment[al] design to evaluate the effectiveness of a variety of asphalt pavement maintenance treatments. During 1999 and 2001, ADOT oversaw the construction of hundreds of experimental sections throughout the state under the Phase I, Wearing Course Experiment (nine treatments and 82 sections at three sites), and the Phase II, Preventive Maintenance Experiment (24 treatments and 137 sections at four sites). Work continued in 2006 and 2007 under the Evaluation of Maintenance Strategies study (SPR 628) for ADOT with a yearlong program of pavement performance monitoring involving manual pavement distress surveys and automated skid, friction and surface texture measurements at all the experimental sites. The project culminated with a detailed analysis of key pavement performance data to compare the performance of the individual treatments and determine their overall effectiveness. This report documents the independent findings of both the Phase I and II experiments.

Indiana

Quantification of the Benefits of Pavement Preservation, Hiral Shah, Yoojung Yoon, Makarand (Mark) Hastak, Jusang Lee and Todd Shields, Indiana Department of Transportation, 2011.
https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1837&context=jtrp
From the summary and conclusions beginning on page 32 of the report (page 38 of the PDF): Through survey and telephone interviews it was found that DOTs use various methods to calculate the benefits of pavement preservation. Currently, INDOT uses lane mile years. It was determined that the Michigan DOT uses a Road Quality Forecasting System (RQFS), Louisiana uses a Highway Health Index, Maine uses [d]TIMS software, Maryland uses lane mile years, and New Mexico and Washington an [a]nnualized [c]osts method to quantify the benefits of pavement preservation. After analysis of these methods, the research team recommended that INDOT use an [a]nnualized [c]osts method for calculating and quantifying the benefits of pavement preservation. A detailed description of the method is presented in this report.

Louisiana

"Field Evaluation and Cost Effectiveness of Crack Sealing in Flexible and Composite Pavements," Momen Mousa, Mostafa A. Elseifi, Mohammad Bashar, Zhongjie Zhang and Kevin Gaspard, *Transportation Research Record 2672*, pages 51-61, 2018.
Citation at https://doi.org/10.1177/0361198118767417
From the abstract: One of the most common methods used to treat longitudinal and transverse cracks is crack sealing (CS), which is categorized as a preventive maintenance method. Field performance and cost-effectiveness of this treatment widely vary depending on pavement conditions and installation of the material. The objective of this study was to evaluate the field performance and cost-effectiveness of CS in flexible and composite pavements in hot and wet

climates such as Louisiana, and to develop a model that would quantify the expected benefits of CS given project conditions. To achieve this objective, 28 control sections that were crack-sealed between 2003 and 2010 were monitored for at least four years. These sections included flexible and composite pavements, sealed and unsealed segments, and varying traffic levels. The performance of these sections was evaluated for the random cracking index (RCI) and roughness index (RI). Based on the results of this analysis, it was concluded that CS only has a significant impact on random cracking. When compared with untreated segments, CS extended pavement service life (PSL) by two years. When compared with the original pavement, CS extended PSL by 5.6 and 3.2 years for flexible and composite pavements, respectively, if applied at the correct time. The cost–benefit analysis indicated that CS is cost-effective whether asphalt emulsion or rubberized asphalt sealant is used. A non-linear regression model was developed to predict the extension in PSL because of CS without the need for performance data based on the average daily traffic (ADT), pavement type and prior pavement conditions.

Michigan

Cost Effectiveness of the MDOT Preventive Maintenance Program, Prashant Ram and David Peshkin, Michigan Department of Transportation, April 2013.
https://www.michigan.gov/documents/mdot/RC-1579_-_Cost_Effectiveness_of_Preventive_Maintenance_421799_7.pdf
The summary of research findings that begins on page 8 of the PDF describes the performance of preventive maintenance treatments. Cost-effectiveness "was determined by calculating a benefit–cost ratio for each treatment, defined as the ratio of the percent area benefit obtained post-treatment compared to the pre-treatment performance divided by the unit cost of the treatment."

Table ES-2, Summary of Pavement Service Life Extensions, and Table ES-3, Calculated Benefit–Cost Ratios for Selected Treatments, on page 9 of the PDF describe findings for:

- Single chip seal.
- Double chip seal.
- Double microsurfacing.
- HMA crack seal.
- HMA mill and overlay.
- HMA overlay.

Performance of the MDOT Capital Preventive Maintenance (CPM) program is addressed on page 10 of the PDF. Table ES-4, Treatment Benefit From CPM Treatments, summarizes the average pavement service life extension and the benefit area obtained from the agency's CPM treatments.

Related Resource:

> **"Performance and Benefits of Michigan Department of Transportation's Capital Preventive Maintenance Program,"** Prashant V. Ram and David G. Peshkin, *Transportation Research Record 2431*, pages 24-32, December 2014.
> https://www.researchgate.net/publication/280160099_Performance_and_Benefits_of_Michigan_Department_of_Transportation's_Capital_Preventive_Maintenance_Program
> *From the abstract:* This paper presents the results of a study performed to calculate the benefits and costs of various preventive maintenance treatments used in MDOT's [Michigan DOT's] CPM program. Defining the benefit as the percent increase in performance over a

"do nothing" or untreated pavement performance curve, where data were available benefits were calculated for preventive maintenance treatments. Using unit costs, benefit–cost ratios were calculated, permitting the comparison of the cost-effectiveness of similar treatments. The overall performance of MDOT's CPM program was also examined by comparing the life cycle costs (LCC) of a rehabilitation strategy to a preservation strategy using a simplified approach. The outcome showed that the preservation strategy results in agency cost savings of approximately 25 percent per lane-mile over a rehabilitation-only strategy. Findings from this study can be used to help MDOT improve its CPM project selection, treatment selection, and performance monitoring and modeling practices.

Capital Preventive Maintenance Manual, Construction and Technology Division, Michigan Department of Transportation, April 2010.
https://www.michigan.gov/documents/mdot/MDOT_CapitalPreventiveMaintenanceManual_322973_7.pdf
Michigan DOT's CPM program includes the following pavement-related treatments:

Flexible and Composite Pavement Treatments

- Nonstructural HMA overlay.
- Surface milling with nonstructural HMA overlay.
- Chip seals.
- Paver-placed surface seal.
- Microsurfacing.
- Crack treatment.
- Overband crack filling.
- HMA shoulder ribbons.
- Ultra-thin overlay.

Rigid Pavement Treatments

- Full-depth concrete pavement repair.
- Concrete joint resealing.
- Concrete spall repair.
- Concrete crack sealing.
- Diamond grinding.
- Dowel bar retrofit.
- Concrete pavement restoration.
- HMA shoulder ribbons.
- Open-graded underdrain outlet cleaning and repair.

The manual provides directives for completing each treatment and includes a description of the expected life-extending benefit to the pavement as a result of the treatment, not the anticipated longevity of the treatment.

Minnesota

Cost/Benefit Analysis of the Effectiveness of Crack Sealing Techniques, Manik Barman, Jared Munch and Uma Maheswar Arepalli, Local Road Research Board and Minnesota Department of Transportation, June 2019.
http://www.dot.state.mn.us/research/reports/2019/201926.pdf
Researchers examined the effectiveness of crack sealing using a benefit–cost analysis, producing two decision trees to assist the agency in choosing the most appropriate crack sealing method.

An evaluation of the cost-effectiveness of two crack sealing methods—rout-and-seal and clean-and-seal—was conducted using a benefit–cost ratio. Researchers examined the cost of each crack sealing treatment individually and then considered all costs incurred during the life cycle (analysis period) of the pavement. The average benefit of the two was considered the "benefit" of the treatment. Researchers' analyses are described in detail in the report:

- The calculation used to determine the unit cost of crack sealing appears on page 93 of the report (page 111 of the PDF).
- An examination of pavement life cycle costs that addresses initial construction costs begins on page 95 of the report (page 113 of the PDF).
- A discussion of maintenance and rehabilitation activities and costs begins on page 98 of the report (page 116 of the PDF).

Cost-Effective Pavement Preservation Solutions for the Real World, W. James Wilde, Luke Thompson and Thomas J. Wood, Local Road Research Board and Minnesota Department of Transportation, September 2014.
http://www.mnsu.edu/ctri/PavementPreservation/PavementPreservationGuidelines-Report.pdf
From the abstract:

> This report presents a summary of pavement preservation activities and recommended uses, expected longevity and expected pavement life extension. It also includes some basic information intended to be used by those less familiar with pavement preservation, pavement management, life cycle cost analysis, cost estimating, contracting methods and others to help inform and educate in this important aspect of pavement engineering. … A set of guidelines was developed as part of the associated project intended to serve as reference material and as a training program.

A discussion of the methods for estimating the costs and benefits of preservation activities begins on page 60 of the report (page 69 of the PDF). As the authors note, "[T]he direct costs of the activities are relatively simple to estimate. The benefits of performing these activities may be less straightforward or direct, at least to determine a dollar value of those benefits."

The authors look at performance as a way to estimate benefits and provide sample data on pavement preservation to illustrate a recommended three-step approach:

- Step 1: Conduct life cycle cost analysis.
- Step 2: Determine total pavement performance value.
- Step 3: Compute cost per performance unit.

Researchers noted that additional questions are not addressed in their analysis:

- Are the additional time and expense involved in extra chip seals and other preventive activities worth the increased pavement performance?
- Are the additional user costs (disruptions to traffic, for example) worth the increased pavement performance?
- How closely can costs and performance be estimated? How much will a change in prices affect the analysis?
- Will delaying preservation activities cause a pavement to deteriorate beyond the point where additional preservation would be useful?

South Carolina

Ranking of Pavement Preservation Practices and Methods, Bradley J. Putman, Jennifer H. Ogle, Yongxi Huang and Logan Reed, South Carolina Department of Transportation, December 2016.
http://www.scdot.scltap.org/wp-content/uploads/2017/02/SPR-695-FINAL-REPORT-Ranking-of-Pavement-Preservation-Practices-and-Methods.pdf
This study sought "to identify methods to improve the implementation of pavement preservation strategies on asphalt concrete roadways in South Carolina," focusing on pavements in the non-Federal Aid secondary system. Researchers recommended adoption of a benefit–cost ratio developed for Nevada DOT, noting that the methodology was effective and simple to implement assuming the availability of the appropriate information. The proposed method appears on page 110 of the report (page 115 of the PDF):

1. Determine the condition of the pavement prior to application of the preservation treatment. If possible, the condition should be quantified by PQI [Pavement Quality Index], however, this must be a measured PQI instead of a predicted PQI. If the PQI cannot be determined due to resource limitations, the surface condition rating should be determined using the guidelines provided in Appendix D [Pavement Condition Evaluation and Treatment Selection Guidelines; see page 147 of the PDF].
2. Apply the appropriate treatment to the pavement and document the actual cost of the application and calculate the unit cost per lane-mile.
3. Measure the pavement condition within a short period of time after the treatment application using the same procedure from Step 1.
4. Regularly measure the pavement condition on an annual basis to establish a pavement condition deterioration curve similar to the examples in Figure 7.1 [see page 111 of the report, page 116 of the PDF].

Texas

"Economic Analysis of Pavement Preservation Techniques," Natalia Zuniga-Garcia, Wilfrido Martinez-Alonso, Andre de Fortier Smit, Feng Hong and Jorge A. Prozzi, *Transportation Research Record 2672*, pages 10-19, 2018.
Citation at https://journals.sagepub.com/doi/10.1177/0361198118768515
From the abstract: This paper summarizes the research study conducted to develop and implement a methodological framework, using an economic analysis technique, to evaluate the cost-effectiveness of the three different preventive maintenance treatments applied to roadways in Texas: chip seals, microsurfacing and thin overlays. The analysis is based on a stochastic evaluation of the effective life and cost of more than 14,000 maintenance and rehabilitation projects undertaken from 1994 to 2015. The effect of traffic loads, traffic volume and roadway type was also evaluated. The life cycle cost of the preventive maintenance techniques was obtained using a Monte Carlo simulation. Among the principal results, it was found that chip seals are the most cost-effective treatment and present the lowest life cycle cost variability. The effective life of all three treatments was found to be quite similar. Additionally, it was found that the chip seals and microsurfacing tend to present comparable life cycle costs when used on heavy traffic roadways.

"Prioritizing Infrastructure Maintenance and Rehabilitation Activities Under Various Budgetary Scenarios: Evaluation of Worst-First and Benefit–Cost Analysis Approaches," Jose Rafael Menendez, Salar Zabihi Siabil, Paul Narciso and Nasir G. Gharaibeh, *Transportation Research Record 2361*, pages 56-62, 2013.
Citation at https://doi.org/10.3141/2361-07
From the abstract: Infrastructure maintenance and rehabilitation (M&R) projects are commonly prioritized using the worst-first (W-F) and benefit–cost analysis (BCA) approaches. While many acknowledge the inherent disadvantages of the W-F approach over the BCA approach, many transportation and public works agencies still use the W-F approach. This paper compares the W-F and BCA approaches in terms of their impact on network condition (specifically, lane-miles in good condition and backlog) under various budgetary scenarios. These comparisons are motivated by the premise that under certain budget allocation and availability scenarios, the shortcomings of the W-F approach may be abated. The analysis presented in this paper uses highway pavement network data from the Bryan district of the Texas Department of Transportation (TxDOT). Bryan district is located in east central Texas (wet-warm climate and generally poor subgrade). In 2011, this network consisted of approximately 3,178 centerline miles. The results suggest that when maintenance and rehabilitation share a single combined budget, the W-F approach is dramatically less effective than the BCA approach in improving the network condition and reducing backlog. However, when the M&R budget is divided into two separate budgets (one for maintenance and one for rehabilitation), the disadvantages of the W-F approach diminish.

Virginia

Best Practices and Performance Assessment for Preventive Maintenance Treatments for Virginia Pavements, Edgar de León Izeppi, Akyiaa Morrison, Gerardo W. Flintsch and Kevin K. McGhee, Virginia Department of Transportation and Federal Highway Administration, August 2015.
http://www.virginiadot.org/vtrc/main/online_reports/pdf/16-r3.pdf
Researchers developed a district-level treatment selection tool "to facilitate the district-level decision-making process. A prioritized list of pavement sections was generated, maximizing the cost-effectiveness of the selected treatments subject to budgetary constraints set by the Central Office. As a pilot implementation, the treatment selection tool was then run for each pavement classification in each district. The results of this pilot suggest that this selection tool has the potential to be a practical decision support tool."

The preventive maintenance treatment selection tool was developed using a Microsoft Excel workbook enhanced with Visual Basic. As the authors note, the tool "applies centrally developed recommendations and allocations for preventive maintenance (PM) with local preferences (e.g., treatment performance and costs) to produce a districtwide preventive maintenance programming aid."

A description of the district-level tool begins on page 25 of the report (page 30 of the PDF). Inputs to the tool include:

- Estimated performance.
    - Preventive maintenance treatment.
    - Do nothing.
- Current-year condition data.
- Cost data.
- Central Office recommendations (total PM lane miles and district budget as derived from PM lane miles).

Washington

Preventive Maintenance Study–Final Report, Keith W. Anderson, Jim Weston, Mark Russell, Jeff S. Uhlmeyer, Kim Willoughby, Dave Luhr and Casey Fraisure, Washington State Department of Transportation, July 2018.
https://www.wsdot.wa.gov/research/reports/fullreports/871-2.pdf
This study evaluated the effectiveness of HMA preventive maintenance treatments at extending pavement life. Researchers used cost data to determine which treatments are the most cost-effective in addressing existing pavement conditions. A summary of the performance of the following preventive maintenance treatment categories begins on page 71 of the report (page 83 of the PDF):

- Crack sealing.
- Full lane chip sealing.
- Wheel path chip seal patching.
- Wheel path chip seal rut filling.
- Crack sealing plus chip sealing.
- Dig outs.
- Dig outs plus crack sealing.
- Dig outs plus chip sealing.
- Blade patch.

The report's primary recommendation is presented on page 87 of the report (page 99 of the PDF):

> The primary recommendation is that preventive maintenance techniques are best applied when distress is first observed. In general, the least expensive techniques of crack sealing and wheel path chip sealing are very effective treatments when the distress is confined to the wheel paths. Full lane chip sealing could be used more frequently than currently utilized because it can mitigate a number of pavement distress conditions, but must be constructed correctly. Dig outs are recommended when the distress is severe but generally confined to small areas. The use of dig outs plus chip sealing is not recommended due to the problems with flushing or chip loss and higher cost. Blade patching is a necessary practice to address specific types of distress such as settlement or a rough ride.

"Evaluation of Maintenance Effectiveness for WSDOT Pavement Network," Jianhua Li, David R. Luhr, Jeffrey S. Uhlmeyer and Joe Mahoney, *Transportation Research Board 93rd Annual Meeting Compendium of Papers*, Paper #14-3468, 2014.
https://pdfs.semanticscholar.org/85d9/16e886f51e91efc8fb0926b4ee126c1efa3b.pdf?_ga=2.213729751.2120952390.1585688037-180670685.1581623323
This conference paper's conclusions described an evaluation of the effectiveness of different pavement maintenance strategies and the comparison of three pavement preservation alternatives and associated costs. Key findings:

- Introduction of the breakeven point to balance the extended life and added cost.
- Improved procedures for analyzing maintenance trade-offs.
- Comparison of possible maintenance scenarios and strategic plans for the Washington State DOT highway network.
- The net equivalent uniform annual cost (EUAC) benefits and benefit–cost ratio is a way to compare different pavement strategies and life cycle costs.
- Applying maintenance treatments early in a performance period is far more effective than applying it to a pavement in poor condition.
- Rehabilitation with well-timed maintenance generates the highest benefit–cost factor. Both maintenance and rehabilitation activities must be considered in the overall life cycle

cost analysis of the pavement strategy since the maintenance will affect the timing of more expensive rehabilitation treatments, even though maintenance is typically much lower in cost.

Related Research

"Incorporating Uncertainties Into Determination of Flexible Pavement Preventive Maintenance Interval," Zhe Han, Juan Diego Porras-Alvarado, Cody Stone and Zhanmin Zhang, *Transportmetrica A: Transport Science*, Vol. 15, Issue 1, pages 34-54, 2019. Citation at https://doi.org/10.1080/23249935.2018.1433730
From the abstract: Continual pavement deterioration creates problems in providing adequate transportation services. Conducting appropriate preventive maintenance (PM) with optimal intervals not only preserves the pavement at a desired performance level, but also provides a cost-effective approach to economizing the maintenance budget. The objective of this paper is to provide a reliability-based framework to determine optimal PM intervals for flexible pavements. The fourth-order method of moments is applied to determine optimal PM intervals based on pavement reliability. The proposed methodology contributes to cases where the distributions for characterizing variable uncertainties are unknown or difficult to identify. The results showed that the proposed method is capable of incorporating uncertainties into the analytical process of obtaining optimal PM cycles through closed-form solutions. The optimal PM interval for the studied newly built pavement is about 7 years. Sensitivity analysis indicates that optimal PM interval increases as PM cost increases, and decreases as rehabilitation cost increases.

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CTC contacted the individuals below to gather information for this investigation.

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Appendix A: Survey Questions

The following survey was distributed to two groups of respondents expected to have knowledge or experience quantifying the benefits of routine and preventive maintenance:

- State departments of transportation.
- Freight, trucking and rail industries.

Quantifying the Benefits of Routine and Preventive Maintenance

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Note: The response to the question below determines how a respondent is directed through the survey.

(Required) Has your agency or organization attempted to translate the specific, quantifiable impacts of routine and preventive maintenance on existing asset condition and/or the overall deterioration of a particular asset? Examples of this type of maintenance include:

Flexible Pavement Maintenance

- Crack seal
- Overlay/leveling
- Profile grinding
- Unpaved travelway repairs
- Dig outs
- Patching potholes
- Other pavement sealing

Bridge Maintenance

- Bridge painting
- Bridge deck repair and overlays
- Bridge spall repair
- Bridge joint seal repair

Transportation Management System Maintenance

- Repair ITS components
- Replace ITS components
- Repair traffic signals

Response options:

- Yes, we have a program that tracks routine and preventive maintenance activities and quantifies their impact on asset condition. (skips the respondent to the eight questions that follow)
- No, we do not have such a program, but we do have plans to institute one. (skips the respondent to the **Wrap-Up** section)
- No, we do not have such a program and have no plans to institute one. (skips the respondent to the **Wrap-Up** section)

1. What successes has your agency or organization experienced in connection with quantifying the benefits of routine and preventive maintenance?
2. If cost savings have been identified, what method was used to determine the savings?
3. If investments were reduced for major capital improvements, what method was used to determine reduction?
4. If asset deterioration slowed as a result of the maintenance activities, how did you determine this result?

5. What challenges has your agency or organization experienced in connection with quantifying the benefits of routine and preventive maintenance?
6. Please describe the tools or methods your agency or organization uses to quantify the impact of routine and preventive maintenance on agency assets, such as a software program, a manual process or other process (please describe the process).
7. Please describe any new tracking and quantification activities your agency or organization is considering that will assess the impact of routine and preventive maintenance on asset performance.
8. Please provide links to documents associated with your agency's or organization's experience with quantifying the benefits of routine and preventive maintenance. Send any files not available online to carol.rolland@ctcandassociates.com.

Wrap-Up

1. Please use this space to provide any comments or additional information about your previous responses.
2. Please provide the name (and contact information, if you have it) of other agencies or organizations you know have experience with quantifying the impacts of routine and preventive maintenance.