

Accelerated Bridge Preservation

Final Report for Project MSU 2018-0074, SPR-1687

April 2020



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| 16. Abstract This project used results of a national survey to collect life expectancies of bridge activities and the durations of construction to do those activities. The national survey also showed the current use of contractors, in-house staff and combinations to execute those activities. In addition, the national survey provided input from 11 agencies on products or processes to speed bridge preservation activities. A second survey of regional bridge engineers in Michigan provided a list of activities and timelines they would use over a 75-year period. A bridge traffic table provides input on traffic for all bridges on the Michigan system. An excel-based tool was developed to evaluate discounted bridge activity costs and user delay costs for bridges in the table. Examples show the effect of discount rate, speed limit, average annual daily traffic, region, and use of modified activity lists. The tool, and especially the use of modified activity lists, allows a region to evaluate user delay costs as well as bridge activity costs for their current practice and for adjustments to that practice. A second tool allows comparison of preservation versus no-preservation activity lists for a user supplied bridge age. Activity costs and User Delay costs are calculated for both scenarios, but decisions in the second tool are based on equivalent annual costs. | | |

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Executive Summary

This project had two goals:

- 1) to identify products and processes that can be used to speed construction of bridge preservation activities
- 2) to provide a tool that would allow region bridge engineers to consider both construction costs and user delay costs in evaluating the activities they plan to do for a particular bridge. This tool can assist in deciding whether bridge preservation should be delayed because of mobility impacts or executed “as planned” to avoid degradation and larger future repairs.

Two surveys provided much of the information necessary to meet these goals: a national survey and a survey of Michigan’s region bridge engineers. Fourteen state agencies responded to the national survey, nine of which are in the wet-freeze climate. Responses were obtained for all seven regions of Michigan.

The nationally distributed survey gathered information about the types of bridge activities that are conducted in various agencies, the life expectancies associated with those agencies, and the duration of construction for each activity. The survey also asked whether each activity was conducted by contractor, state in-house forces or a combination of the two. In addition, the survey asked for any products or processes that the agency uses to speed construction of bridge preservation.

The list of bridge activities included treatments ranging from bridge washing (maintenance) to epoxy overlay (capital maintenance or preservation) to deck replacement (rehabilitation) to bridge replacement (reconstruction). A total of 41 activities were included in the survey. For example, for the activity of joint sealing/repair, Kansas Department of Transportation (DOT) indicated that the treatment would have a service life of between 2 years and 15 years, and would take between 3 hours and 1 workday or work-night to construct. Kansas DOT uses a combination of state forces and contractors to conduct joint sealing/repair. For deep concrete overlay treatment, Kansas DOT indicated a life expectancy of between 15 years and 30 years, with 3 to 6 months required for construction, and the work done solely by contractors.

Construction durations could be entered for both moderate average annual daily traffic (AADT) and high AADT. Obtaining information on construction duration was critical in order to estimate user delay time and cost. The responses from the national survey were compiled into lowest low value, highest high value and average values of life expectancy and construction duration for each activity.

The survey of region bridge engineers in Michigan DOT asked them to react to the results of the national survey. For each activity life expectancy, they were asked to either agree or provide their own expected life for the treatment. Michigan region bridge engineers predicted shorter treatment life for approach joints, joint repair, deck crack sealing, healer sealer and spot painting but agreed with the national survey regarding epoxy inject cracks, superstructure wash, deck wash, drain clean and lubricate bearings, to name a sample of the treatments. While there are comments regarding the construction duration of some of the activities, Michigan region bridge engineers generally agreed with the results of the national survey.

The Michigan-only survey also asked the region bridge engineers to create a list of activities over a 75-year cycle of activities they would do and when. Up to five activities could be assigned in any year. Most of the regions centered their activities at regular time intervals. Most were at 10 year intervals, but there was significant variation between regions. For example, University region included joint seal/repair at 5-year intervals. Superior and North regions included cyclical maintenance and preservation treatments including bridge deck washing, joint seal repairs, and healer sealer or epoxy overlays. The most populous regions, Grand and Metro, spread treatments out, and included fewer preservation treatments. One important point about the activity lists: they do not assure that bridge conditions are equivalent between regions. Instead, they reflect bridge management approaches by each region.

A tool was developed for this project that calculates the discounted bridge activity costs and user delay costs for a bridge of interest over the 75-year period. The activity list for the region in which the bridge is located is used. Bridge information regarding average daily traffic, percentage commercial traffic, traffic growth rates, speed limit, deck area, and number of lanes is looked up in the bridge traffic table compiled for the project. The analyst inputs only the structure number from the bridge traffic table and the discount rate.

The tool uses the region's bridge activity list, the unit costs of activities from NCHRP and the bridge size to calculate the total cost of each activity. The tool uses present worth life cycle cost analysis in which all future costs are brought to the present time using the provided discount rate. The resultant for all the activities in the 75-year period is the Bridge Activity Cost (BAC). The tool uses the traffic information and the activity durations to produce a User Delay Cost (UDC) that considers the delays to automobiles and commercial vehicles for reduced speed in travelling through the workzone as well as time spent in the queue, if one develops.

The tool is Excel-based and consists of 11 macros written in visual basic for applications (vba). The tool includes the complete bridge traffic table, individual region bridge traffic tables, activity lists for all regions, a table of hourly average traffic distribution fractions for Michigan, a table of activities and their unit costs and durations. The user initiates the analysis from the output page by providing the bridge number. The output page automatically is filled with the region, route, number of lanes and other pertinent identifying information. Following input of the discount rate, the BAC and UDC values are included in the output page. An additional worksheet is provided for facilitate modification of the activity lists, allowing a region bridge engineer to evaluate BAC and UDC for various activity lists.

Numerous examples are included that demonstrate some of the key variables that impact BAC and UDC. The impact of discount rate is significant. If the discount rate is equal to zero, then there is no time-value of money and the activity costs are simply the sum of the costs. As the discount rate increases, the impact of future expenditures decreases. Since both BAC and UDC are discounted, both decrease with increasing discount rate. The impact of discount rate was demonstrated for two bridges in two regions, with discount rates between 0.02 and 0.04. The discount rate used in the analysis should be the discount rate used by an agency for their pavement type selection process, but should be reviewed and updated regularly.

Speed limit impacts user delay costs significantly. When speeds are lower, the road and bridge capacity per lane is decreased. Queues form more quickly and are sustained longer before dissipating. An example shows the impact of speed limits on a single bridge, when speed limits vary between 35 miles per hour and 70 miles per hour.

Average daily traffic changes were also demonstrated on a two-lane bridge with a 70-mile per hour speed limit. Because the same bridge was used for all four speeds, the bridge activity cost was constant. As expected, as the volume of traffic increases, the user delay costs increase significantly.

Modifying bridge activity lists provides a bridge manager the opportunity to try various lists of treatments to see their impact on BAC and UDC. Several examples are described. In one case, additional preservation treatments were added and using these pushed out some treatments to later years. The result was a decrease in BAC but an increase in UDC. An example using Southwest region showed a decrease in both BAC and UDC with the modified activity list. Another case, using the North region activity list resulted in both higher BAC and higher UDC. Finally, the very detailed activity list submitted by Superior region was modified to provide 3-year periods between bridge activities. This modification resulted in substantially lower BAC and UDC.

A single bridge was evaluated with five regional activity lists, holding all aspects of the structure constant. Clear differences were present in both BACs and UDCs. The BAC varied between \$193,648 from North region to \$343,805 from Metro region. User delay costs ranged between \$385,483 for University region and \$1,306,125 from Grand region. As mentioned earlier, using different activity lists does not assure that each list produces comparable bridge conditions. With this said, the tool allows region bridge engineers to ask “what if” regarding both activity costs and user delay costs.

A second tool, Tool2, compares the equivalent annual cost of BAC and UDC for two sets of activities: one with capital maintenance/preservation and one with no preservation. The activity list for the preservation case extends to 105 years. The activity list for the no preservation case extends to 80 years, but the first 25 years of the activity list was appended to reach 105 years. While not “economically pure”, this approach allowed evaluation of bridges up to 79 years old. Bridge reconstruction occurs as the last activity for the preservation case and at 80 years for the no-preservation case. Because of the difference in time to reconstruction, equivalent annual costs are used instead of a present worth calculation used in Tool2. Tool2 is intended for use on existing structures, and the analyst enters the bridge age. The goal of Tool2 is to allow consideration of both activity costs and user delay costs in evaluating whether to use preservation or use a no preservation approach. An example is included to show the impact of bridge age on EAC-BAC and EAC-UDC for both preservation and no preservation cases. EAC-BAC increases with increasing bridge age, while EAC-UDC decreases due to decreased traffic growth for the older bridge.

Chapter 1 Purpose, Scope and Tasks

Purpose

This project began with a situation faced by Michigan DOT: region bridge engineers were sometimes opting out of preservation treatments in favor of rehabilitation or reconstruction due to the adverse impacts of work zones on the traveling public. While it is known that preservation can result in lower life cycle costs over the life of a bridge with improved bridge conditions over a longer period of time, the effects of user impacts are not part of the life cycle calculation. The goal was to create a decision making tool that would allow consideration of both life cycle cost and user impacts for a variety of scenarios including preservation, rehabilitation and reconstruction.

In addition to development of a decision making tool, the research panel also desired information from other agencies about techniques, products and processes they used to speed construction of preservation treatments.

Scope

Michigan DOT's Office of Structure Preservation and Management developed the Research Needs Statement (RNS) for the Accelerated Bridge Preservation project. The RNS described situations where region bridge engineers opted to forego bridge preservation projects, waiting for more comprehensive and costly bridge rehabilitation or reconstruction projects. A decision tool that considers both bridge life cycle cost and user impacts is the desired product of the Accelerated Bridge RNS. Identification of potential products, processes and treatments that would speed construction of bridge preservation projects was a second important project goal. The Accelerated Bridge Preservation RNS was selected from a group of submitted RNSs for funding under the Michigan DOT's research program, and a Request for Proposals was issued. A team from the National Center for Pavement Preservation at Michigan State University responded to the RFP and was selected to perform the work.

A survey had been conducted by the Midwest Bridge Preservation Partnership asking respondents which of a list of bridge treatments they used. For each treatment used, the respondents gave an expected treatment life. Michigan DOT had a few additional bridge treatments that were added to the list. That list became the list of treatments for the literature review as well as the list of treatments for the national and Michigan surveys. The list of treatments is shown in Table 1.1: Bridge Activities. The treatments range from the most basic preservation via approach pavement relief joints and joint sealing/repair, through more complex activities like full depth patching, to replacement of sub or super structures, and finally to full reconstruction.

| Bridge Activities from Preservation to Replacement | | | | | |
|--|------------------------------------|----|-------------------------------|----|--------------------------------|
| 1 | Approach pavement relief joints | 16 | Lubricate bearing and seat | 31 | Paint-complete |
| 2 | Joint sealing/repair | 17 | Level bridge approach | 32 | Paint-zone |
| 3 | Deck Crack Sealing | 18 | Bridge barrier railing repair | 33 | Pin & hanger replacement |
| 4 | Epoxy Inject Superstructure Cracks | 19 | Thrie beam retrofit | 34 | Bridge barrier railing replace |

| Bridge Activities from Preservation to Replacement | | | | | |
|--|-----------------------------------|----|---|----|----------------------------|
| 5 | Healer sealer | 20 | Deck patching-partial depth | 35 | Bearing replacement |
| 6 | Coat concrete barrier/deck fascia | 21 | Deck patching-full depth | 36 | Drain system replacement |
| 7 | Coat concrete substructure | 22 | Patch superstructure spalling | 37 | Approach slab replacement |
| 8 | Coat concrete beams | 23 | Deck patching-partial depth | 38 | Deep concrete overlay |
| 9 | Seal abutments and caps | 24 | Deck patching-full depth | 39 | Major substructure repair |
| 10 | Metal mesh panels | 25 | Patch superstructure spalling | 40 | Superstructure repairs |
| 11 | Spot painting | 26 | Minor substructure patching | 41 | Substructure replacement |
| 12 | Superstructure wash | 27 | Joint replacement | 42 | Deck replacement |
| 13 | Deck cleaning/washing | 28 | Epoxy overlay | 43 | Superstructure replacement |
| 14 | Drain system clean/repair | 29 | HMA overlay with waterproofing membrane | 44 | Bridge replacement |
| 15 | Clean and reset bearings | 30 | HMA overlay with no membrane | | |

Table 1:1 Bridge activities

Tasks

In the accepted proposal for the Accelerated Bridge Preservation project, the team identified tasks to complete the project. These were modified based on comments and suggestions from the research panel at the kickoff meeting and further modified as the work progressed. The decision making tool will consist of a life cycle calculation based on anticipated treatments and timing over the life of the bridge and a user impact calculation based on the duration of construction and type of traffic control necessary for the treatments in the life cycle cost calculation.

The first task of most research projects is a literature review. In this case, bridge preservation literature was evaluated and grouped according to the activities in Table 1.1. Of particular interest were techniques and products that speed up the construction of bridge preservation projects. The literature review also included bridge life cycle cost analysis and quantification of user impacts.

As mentioned earlier, the Midwest Bridge Preservation Partnership had conducted a survey of treatments used by member agencies and the expected life of those treatments. A national survey was proposed as Survey 1 in this project. It asked agencies to identify treatments they use and the range of expected lives they have experienced. They were asked for the construction duration for each treatment, and whether the work was performed in house or was contracted. The survey requested information about methods and products used to speed preservation activities, and about the type of traffic control used for particular durations of work.

A second survey to be completed by Michigan DOT region bridge engineers was developed using the results of Survey 1. The respondents were asked to agree or disagree with the ranges of life expectancies and construction durations for the activities in Table 1.1 from the national responses. If they disagreed, they were asked to provide the range they thought most appropriate. Michigan DOT has recommended timing for preservation activities, but the research team realizes that budget restrictions and local priorities may impact the actual timing. Survey 2 asked the region bridge engineers to indicate when various activities would most likely occur over the 75-year life of a bridge. The results of Surveys 1 and 2 provided the input for both the life cycle calculation and the user impacts calculation.

A third survey was focused on unscheduled bridge activities. In many cases, these would be caused by accidents or critical needs identified by inspectors or even reports from casual observers, but in any case, they cause driver delay or detours. This Michigan-only survey was to estimate the user impacts from unscheduled activities. This survey proved to be unsuccessful in gaining helpful information about user impacts.

Case studies were developed for a number of scenarios. One example includes the BAC and UDC for a single bridge for discount rates varying from .02 to .04. Another example considers the impact of speed limit, which determines the road capacity and therefore, queueing during construction. In addition, an example modifies the average daily traffic level for a single bridge. This modification impacts the user delay costs but not the activity costs. An example with modification of the activity lists for four regions completes the examples for Tool1. Tool2 uses equivalent annual cost of BAC and UDC for preservation case and the no preservation case. An example demonstrates the impact of bridge age on EAC-BAC and EAC-UDC for both cases.

Organization of the Report

Chapter 1 of the final report outlines the problem, scope of the research, and tasks undertaken in general terms. Michigan DOT wants a tool that will allow bridge management decision makers to consider both life cycle costs and user impacts in deciding whether to conduct or defer bridge preservation treatments.

The literature review is contained in Chapter 2. The literature review and the associated references are divided by maintenance, rehabilitation and reconstruction tasks. Literature and references used in developing the user delay costs is included in the literature review.

The national survey and its' results are described in Chapter 3. This survey includes activities that range from basic bridge cleaning, through capital maintenance, rehabilitation and bridge replacement. For each activity, respondents were queried regarding the expected life of the treatment, the duration of conduct of the treatment construction, and traffic control needs. This survey also requested information about products and processes used to speed bridge preservation activities. These are presented in Chapter 4.

The Michigan-only survey of region bridge engineers is described in Chapter 5. One of the key results of this survey was the list of anticipated activities and their timing over a 75-year period. The region bridge engineers were asked to respond regarding the activity durations from the national survey, and their general agreement with those duration ranges allowed these durations to be used in developing the user delay tool.

Chapter 6 describes the analysis Tool1 for life cycle cost and user impacts based on the surveys. The tool is an Excel based tool written in visual basic for applications (VBA). A table of Michigan DOT bridges can be used by region bridge engineers to select a bridge of interest. That table also provides the bridge region, county, deck area, speed limit, average daily traffic and other inputs used in the tool. The activity list is selected based on the region and traffic level (both Grand and Metro regions have two activity lists based on number of lanes; other regions have a single activity list for all bridges).

Chapter 7 demonstrates the tool and its results for several case studies. Two case studies compare the impact of activity lists across regions using similar traffic levels. Alternate activity lists were developed for four regions and the results of those, in comparison to the region's activity list are included in another case study. Finally, the impact of speed limit is demonstrated for the Bay region and the impact of traffic level is demonstrated for the Grand region. In the case studies, both PW and UDC are presented.

Chapter 8 describes analysis Tool2 for considering preservation and no preservation activity lists for a single bridge. An example is included demonstrating the impact of bridge age on the EAC-BAC and EAC-UDC for both lists.

Chapter 9 provides conclusions and recommendations as well as proposed implementation activities.

Appendices contain the definitions of variables from the analysis tool, logic and operations for both tools and the visual basic for applications (vba) code.

Chapter 2 Literature Review with Notes on Michigan Practices

This literature review covers the broad range of bridge treatments that were included in the survey of states. The following treatment topics included in this document have been combined to reflect research reports:

- Joints (including sealing, repair, replacement and removal),
- Deck sealing,
- Crack injection of Superstructure,
- Coatings and Painting,
- Resetting and replacing bearings,
- Deck and superstructure washing,
- Cleaning and repair of drain system,
- Partial and full depth patching including deck, substructure and superstructure,
- Deck overlays,
- Deck replacement, and
- Pin and hanger replacement.

Missing from the literature were approach and leave slabs, metal mesh panels, Thrie Beam retrofit, and bridge barrier railing repair and replacement.

The remaining items in Survey 1 are clearly beyond bridge preservation and belong in rehabilitation or reconstruction. A final topic area of this literature review includes some emerging technologies that have shown promise and that may enable agencies to expedite the application of future treatments.

In many states, bridge preventive maintenance or bridge preservation strategies, materials, and technologies have been developed in response to the very high cost of using a “replacement only” approach to the bridge inventory. For example, most of the Kentucky Transportation Cabinet’s (KTC’s) inventory of about 10,000 bridges are at least 50 years old. Funding is insufficient for large-scale bridge replacements, so KTC has identified eight bridge preventive maintenance activities:

1. Resealing and repairing joints,
2. Cleaning and sealing bearings,
3. Bridge washing,
4. Sealing decks,
5. Spot painting,
6. Patching bridge decks,
7. Cleaning and painting pier caps and abutments, and
8. Scour, drift, sediment, and bank stabilization (1).

The American Concrete Institute (ACI) has also developed a guide for maintenance of concrete bridge members. The maintenance activities include sealing, washing, caulking, crack repair and other similar treatments to prolong the functionality of concrete members (2). The American Association of State Highway & Transportation Officials (AASHTO) has a current project to develop a guide for bridge preservation actions. The contractor for the guide development is George Hearn with the University of Colorado at Boulder, and the work is scheduled for completion by mid-2019 (3). These efforts demonstrate the importance of bridge preservation and the desire for high quality, early-life treatments.

We found only very limited information on accelerating bridge preservation or capital maintenance. When such items were found and used in the literature review, they are italicized.

References:

1. Meade, Bobby; Wells, Danny; Palle, Sudhir; and Hopwood, Theodore, II; “*A Programmatic Approach to Long-Term Bridge Preventive Maintenance*”, University of Kentucky, Lexington, Lexington, KY, Report KTC-16-22/SPR15-504-1F, April 2016.
2. “*Guide to Maintenance of Concrete Bridge Members*”, American Concrete Institute, Farmington Hills, MI, Report 345.1R-16, September 2016.
3. “*Proposed AASHTO Guide for Bridge Preservation Actions*”, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., Project 14-36.

Joint Repairs and Replacement

The purpose of a bridge joint is to accommodate movements resulting from temperature changes and creep and shrinkage of concrete. Joints are frequently designed to protect the interior edges of concrete decks from vehicle loads and seal the joint openings. Expansion joints are often one of the first components of the bridge to fail. Due to increasing use of chlorides and other corrosive materials to maintain “bare decks” during winter snow and ice, failed joints can allow damage to bridge superstructures and substructures including rusting of beam metal bearings, early advanced corrosion of beam ends, spalling of precast beam ends, concrete abutments and concrete piers (1). Notwithstanding the severe damage that can result from joint failures, most agencies undertake joint repair and rehabilitation only when it is associated with deck rehabilitation (2). Table 2.1, below, includes basic information on the joint types described in this section.

| Type | Movement Range (inches) | Notes |
|--|-------------------------|---|
| Plug Joints | ≤ 1 | Backer rod and elastoplastic bituminous binder |
| Pourable Joints | ≤ 1 | Backer rod and waterproof sealant |
| Compression | ≤ 2.5 | Closed-form foam |
| Open (Butt) | 2-3 | With or without troughs |
| Strip Seal | 3-4 | Neoprene membrane attached to side rails; avoid splicing membrane |
| Sliding Plate | 1-3 | Michigan restricts use to sidewalk bridges |
| Finger Joints | >3 | Fingers may bend or break off during snow/ice removal operations |
| Reinforced Elastomeric (modular joint) | 2-6.5 | Sheet seals with cast-in-place studs |

Table 2.1 Summary of Bridge Joint Types and Accommodated Movements

Work by Shenton, et al. (3) described key expansion joint types used to accommodate small movements in bridges. Asphalt plug joints can accommodate joint movements up to 1 inch. Compression seals can accommodate movements up to 2.5 inches, while bonded joints can sustain movements of 3 to 4 inches. Strip seal joints allow up to 3 to 4 inches of movement. Pourable joints can accommodate movements up to 1 inch. Open joints (which are also called butt joints) can allow joint movements up to 2 to 3

inches. They are usually armored to protect the top edges of the concrete deck and sometimes configured with a sliding plate or fingers.

Open joints do not prevent the intrusion of water although some are fitted with troughs to drain any entering water. When a trough is used, slope protection may be required beneath the bridge to avoid erosion during heavy rains (1). Difficulties in maintaining and cleaning troughs on finger joint bridges led Steinberg, et al. (4) to recommend consideration of the use of foam inserts, side flaps, and concrete troughs cast into bridge abutments or piers.

The selection of the joint type is a function of the magnitude of movement expected to occur. For short deck lengths (and usually low volume roadways) with an expected movement of less than one inch, an open joint or butt joint may be used. For movements of one to three inches, a sliding plate joint may be used. These joints are used less often due to long term performance issues including fracturing or corrosion of the plates that render them immobile. (Michigan DOT restricts their use to sidewalk bridges.) Incompressible debris can accumulate at the end of the plate, limiting its movement. This reduction in joint movement was reported by Iowa DOT (1). While the plate joint allows water (with chloride ions) to enter the joint, it does provide some protection against the entry of debris. For movements larger than three inches, finger joints can be used. Proper installation and a straight joint construction are necessary to prevent the fingers from jamming. The finger can also bend or break off. Like the sliding plate, the finger joint provides some protection from debris entering the joint.

Closed joints are designed to prevent water with damaging chlorides and debris from entering the joint and damaging the superstructure and substructure elements beneath the joint. The debris that collects on pier caps or around bearings holds moisture and damaging salts, accelerating corrosion. Closed joint types are based on expected movements. For small movements of less than 0.25 inch, a poured seal consisting of a backer rod and waterproof sealant may be specified. For movement less than two inches, either an asphalt plug joint or a compression seal could be used. The asphalt plug joint consists of a backer rod and an elastoplastic bituminous binder. There are differences in recommended limits of movement between various researchers in this area.

Compression seals are either neoprene or cellular and depend on remaining compressed against the sides of the joint to stay in place and be effective. Strip seals can be used for movements up to four inches and consist of a flexible neoprene membrane that is attached to two opposing side rails on the ends of the two adjacent deck slabs. Iowa reported that the failure of neoprene strip seals typically occurs at about 15 years, while compression seals typically fail at 10 years. Spalling of the concrete on either side of the expansion joint was also noted (1).

Compression set in closed-form foam bridge expansion joints was studied by Sparacino, et al. (5). They concluded that the current test protocol is very different from what the foam will experience in service. Specifically, they recommended that the effect of compression duration, temperature and recovery duration should all be considered in evaluating the impact of compression set on the tensile capacity of the sealed joint.

Iowa DOT has been experimenting with Silicoflex expansion joint, a seal that can be installed on any flat vertical face of the joint and uses a neoprene seal with adhesive on the vertical faces. As a result, it can be used to replace a failed compression or strip seal without removing concrete or steel sections of the joint. The absence of concrete demolition and construction, reduced cure times and ease of installation shows promise. The manufacturer estimates installation time at 30 minutes per lane. (1)

Reinforced elastomeric joints, a type of modular joint, consisting of sheet seals with cast-in-place studs, can accommodate movements of between two and 6.5 inches. Finally, for large joint movements of four to 24 inches or larger, modular elastomeric joints can be used. These complex joint structures consist of sealers, separator beams, and support bars. (Brown and Guthrie, 2011). Modular elastomeric joints have experienced fatigue cracking of welds, damage to equalizing springs, damage of the neoprene sealer material and damage to supports (2).

The strip seal received the most positive appraisals of any joint type in the 2003 Synthesis (2). While they tend to have a longer life than other joint seals, they can be difficult to replace and splicing of the membrane should be avoided. They should not be used on bridges with skew angles approximating those of snowplow blades.

The most common mode of closed joint failure was tearing and seal separation. Debris accumulation contributes to tearing. Snow plow damage was also reported. Joints and armor should be recessed 1/8 inch to 5/32 inch below the deck surface to minimize snow plow damage. Troughs need an 8 percent slope to carry water, chlorides, and debris away from the joint.

A 2005 Utah Study of freeze-thaw states indicated that typical joint movements ranged from 1 to 4 inches. Strip seals, followed by finger joints, were the most common joint types used. Half of the respondents indicated that they replaced compression seals and sliding plates with strip seals during bridge or deck rehabilitation (6).

The goal of modern joints is to “have a joint that is quiet, smooth riding, watertight, capable of accommodating movement, as durable as the adjacent deck, and as maintenance free as possible” (2). While maintenance-free joints are not the current state of practice, preventive maintenance can extend the period of satisfactory performance of expansion joint seals. The needed preventive maintenance includes washing decks, keeping deck drains open, removing debris, and fixing small joint system problems before failure occurs. The seal should be repaired if any part is leaking. If a blockout is to be constructed, it must be cast to uncontaminated and sound concrete (2).

Integral abutment joints provide for bridge movement at the junction of the abutment and the approach slab. Iowa uses tire buffing material and silicon sealant to fill the joints, which can be readily repaired by adding additional buffing material and sealant. Erosion from the runoff at the end of the bridge is a secondary issue with this joint type (1).

Iowa DOT had a project to explore approaches for accelerating the replacement of bridge deck joints. In reviewing the time required for various tasks in replacing a bridge deck joint, they found that demolition comprised the largest portion of the time, followed by formwork and rebar placement and concrete placement and curing. They found it infeasible to significantly reduce formwork and rebar placement given the wide variation in bridges and minor adjustments made to more standard bridges during

construction. Phase 2 was not funded. In the Phase 1 Report, the following options are presented and may apply to other types of preservation treatments beyond just joint replacement (1):

- Pre-development of maturity curves for concrete materials that will reach the required compressive strength in 9 to 12 hours.
- Placement of traffic control for a ramp joint replacement took 4 hours to complete. Combining equipment mobilization with this time could reduce construction time.
- Use of premade, or at least precut, formwork to speed form construction.
- Reconsideration of the existing requirement to retain the existing vertical reinforcing bars during demolition and instead use drilled holes and epoxy to embed reinforcement in the existing footing.
- Use of a detour, when feasible, can eliminate extra paving to accommodate traffic and speed construction.
- Significant production differences for experienced versus inexperienced crews, especially with regard to formwork and rebar installation.
- Minimization of staging, which is expensive and adds extra cost for traffic control and extra time to complete the work.
- Understanding that narrow bridges are a significant challenge, especially when there is no feasible detour route.
- Temporary barriers separating moving traffic from construction use up between 1 foot 10.5 inches for precast concrete and 1 foot 1 5/8 inch for steel barrier rails.
- Use of mechanical splices instead of lap splices to reduce the amount of concrete demolition required to splice new rebar into existing rebar. Mechanical splices may not be feasible however, due to their bulk and the requirements for adequate concrete cover.
- Eliminate strip seal upturn at gutter. Would require development of a drainage system.
- Evaluate type of concrete needed for each application. Only use 8-hr concrete where truly needed and use 24-hr on an extended closure.

The issues with joint performance and maintenance have led to efforts to eliminate existing joints by several agencies. Mahmoud, et al. (7) evaluated temperature shifts and thermal gradients by instrumenting typical steel and concrete bridges in Colorado. They found that despite the joints being clogged, some movement occurred that caused changes in stress in the underlying girders. Based on life cycle cost analysis, they found that eliminating joints would reduce the life cycle cost of the bridges.

Joint elimination is achieved by constructing continuous decks or closure pours. To minimize cracking in the deck, low-permeability fiber-reinforced concrete was reported by Ozyildirim, et al. (8). Three different fibers were used: polyvinyl alcohol, polypropylene, and 5D steel fibers. High volumes of fibers were needed to sufficiently control cracking, so that multiple very tight cracks (<0.1 mm wide) occurred.

Notes on Michigan Practices:

Based on the results of Survey 2 (see Chapter 5 for details), cyclic joint sealing and repair is conducted on a 3-year cycle in Superior region and on a 5-year cycle in University region. Joint sealing and repair was conducted at 10 years in Southwest region and at 15 years in Bay region. Joint replacement

occurred at 15 years and 30 years in Grand region. Joint replacement at 20 years was common and was reported by University, Bay and North regions. Joint replacement would also be triggered by placement of a deep concrete overlay or a deck replacement. Deep concrete overlays were planned by Superior region at year 45 and by Bay at year 50. Timing of deck replacements varied, with Metro region at year 50, Grand and Superior at year 55, and Bay and University at year 60.

References

1. Miller, Adam M. and Jahren, Charles, T, “*Rapid Replacement of Bridge Deck Expansion Joint Study- Phase I*”, Institute for Transportation, Iowa State University, Ames, Iowa, Dec. 2014.
2. Purvis, Ron, “*Bridge Deck Joint Performance*”, National Cooperative Highway Research Program Synthesis 319, Transportation Research Board, Washington, D.C., 2003.
3. Shenton, Harry W, III, Mertz, Dennis R., and Weykamp, Peter J., “*Guidelines for Maintaining Small Movement Bridge Expansion Joints*”, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.; Report NCHRP 12-100; September 2016.
4. Steinberg, Eric; Walsh, Kenneth; and Sparks, Nik; “*Bridge Trough Maintenance Evaluation on Finger Joint Bridges*”; Ohio University, Athens; Athens, Ohio; Report FHWA/OH-2015/35; Feb. 2016.
5. Sparacino, Matthew G; Shenton, Harry W.; and Weykamp, Peter; “*Compression Set in Closed-Cell Foam Bridge Expansion Joints*”; Journal of Bridge Engineering; American Society of Civil Engineers; Volume 23, Issue 1; October 2017.
6. Brown, Michael C., and Guthrie, W. Spencer, “*Concrete Bridge Deck Joints: State of Practice*”, presented at the Southeast Bridge Preservation Partnership Meeting and available on the TSP2 website, Raleigh, NC, April 14, 2011.
7. Mahmoud, Hussam; Atadero, Rebecca; Rager, Karly; and Smith, Aura Lee Harper; “*Joint Removal Implications - Thermal Analysis and Life-Cycle Cost*”; Colorado State University, Fort Collins; Fort Collins, CO; Report 2018-02; April 2018.
8. Ozyildirim, H. Celik; Khakimova, Evelina; Nair, Harikrishnan; and Moruza, Gail M.; “*Fiber-Reinforced Concrete in Closure Pours over Piers*”; ACE Materials Journal; American Concrete Institute; Volume 114, Issue 3, pp 397-406; May 2017.

Concrete Deck Sealers and Crack Sealers

Concrete deck cracks can be caused by cement mortar shrinkage, freeze-thaw cycles, thermal stresses, or settlement and traffic loading. Transverse cracks, which are most common, are caused by a combination of shrinkage and thermal stresses.

Cracks allow accelerated ingress of water and chloride ions, which can penetrate to the level of reinforcing steel. Once this level is reached in sufficiently high concentrations, a corrosion cell is started with the steel, leading to corrosion of the steel rebar section. Rebar strength is lost, and the corrosion products expand, introducing tension into the concrete, delaminations, and ultimately, surface spalls. Many factors influence the rate at which chloride ions penetrate the concrete including the water cement ratio, admixtures, air content, density, age, supplemental materials like coal fly ash or blast furnace slag, coverage depths, the type of reinforcing steel, the use of epoxy-coated reinforcement, and other construction variables (1). In addition to degradation caused by chloride ions, water that enters the

cracks, if subjected to freezing, will expand by about 7% and cause additional cracking or widening of existing cracks in the concrete.

Water and chloride ions can penetrate the concrete cracks by capillary absorption, hydrostatic pressure, and diffusion. Because water does not normally stand with significant hydrostatic head on a bridge structure, this is a minor component. Capillary absorption occurs due to repeated wetting and drying, which is a frequent occurrence in wet climate regions. Diffusion occurs due to the different chloride concentrations with depth in the concrete. Both capillary action and diffusion tend to increase chloride concentration over time and over depth (1).

Cracks need to be sealed to prevent ingress of chloride-ion water that causes rebar corrosion. The onset of corrosion is delayed by use of epoxy-coated reinforcing steel, but construction and handling frequently cause nicks in the epoxy coating. Corrosion begins at these defects. Therefore, sealer effectiveness can be expressed in terms of the reduced ingress of chlorides, the existence of enough penetration of the sealant to protect the surface even under traffic abrasion and having enough effective sealant service life to minimize the number of applications (2). A summary table on deck and crack sealants is provided in Table 2.2. Healer sealers are very low viscosity, liquid applied resins. Types include MMA, HMWM, epoxy and polyurethane. Silanes and siloxanes are penetrating sealers.

| Type | Notes |
|--|--|
| Healer sealer | Michigan uses flood coat; 1 day treatment |
| mma (methyl methacrylate) | Rapid setting concrete patching material |
| HMWM (high molecular weight methacrylates) | Ultra-thin cracks; adhesive |
| Epoxy | Ultra and very low viscosity epoxy |
| Polyurethane | |
| Epoxy overlay | Michigan uses 2-coat epoxy overlay with 3-day construction |
| Linseed oil | Most commonly used for scaling |
| Silanes | Penetrating sealer; may be 40% solids or 100% solids; used by Caltrans as surface sealer with HMWM as crack sealer; performed better than Siloxanes in Nevada study. |
| Siloxanes | Also, a penetrating sealer. |

Table 2:2 Deck and crack sealant summary table

The most common deck and crack sealants are high molecular-weight methacrylates (HMWMs), epoxies, linseed oil, and silanes and siloxanes. In the survey of state practice conducted by Krauss, Lawler and Steiner, epoxy injection crack repair was the most common crack sealing method, followed by HMWMs (3). HMWMs are adhesives composed of methacrylate monomers that have been subjected to an oxidation-reduction chain reaction to become a high molecular-weight polymer. HMWMs have been used by Caltrans since 1981. Epoxies, of which there are many formulations, are structural adhesives. Use as a deck sealer was reported by New Jersey's Highway Authority in 1959 and 1960. Linseed oil is commonly used for scaling of bridge decks but is present in standard specifications

for crack sealing. Silanes and siloxanes are derived from silicone with molecules small enough to penetrate cracks. They bond to the concrete and form a hydrophobic layer that reduces water inflow (4).

Both methacrylate (mma) and HMWMs penetrate the concrete surface more than epoxy sealers. A Wisconsin study rated potential products according to the following priorities:

1. Time to open to traffic,
2. Expected durability,
3. Surface preparation requirements,
4. Environmental application conditions,
5. Coverage rate and cost, and
6. Freeze-thaw resistance.

It was noted that the time to open to traffic can vary significantly. Drying and curing time ranged from 45 minutes to 12 hours. The Wisconsin study pointed out that manufacturers do not typically test sealants for freeze thaw resistance. The study measured chloride concentration with depth and measured the penetration of the sealants using a dye method for deck sealants. Crack sealants were evaluated based on their ability to penetrate and fill cracks of various widths and for bond strength and durability of the sealants both with and without freeze-thaw conditioning. In this laboratory study, a portion of specimens were subjected to freeze-thaw cycles prior to testing for chloride ion content. A 20 to 30 percent decrease in bond strength was typical after freeze thaw conditioning (5).

Different waterproofing membranes were tested by Xi, et al. (6) for Colorado Department of Transportation. The products varied considerably. Bridge Preservation TM is an elastomeric spray-applied waterproofing system. Polyguard is a rubberized asphalt waterproofing adhesive that is laminated to polypropylene sheet membrane. Protecto Wrap is a rubberized bituminous resin that is cold applied as a self-adhering sheet membrane that would then be covered with a wearing course. Sikadur is a two-part epoxy compound. The study showed that all the products provided control of moisture, but not of chloride concentration. Bridge Preservation TM provided the best performance according to the research team.

An earlier field evaluation of four sealer products for Colorado Department of Transportation by Liang, et al. (7) recommended HMWMs over the two epoxies and a silane product based on skid resistance, moisture fluctuations and chloride profiles.

Recent research for Nevada Department of Transportation evaluated five deck sealers and six crack sealers for two types of concrete common in northern Nevada. The best performance was for Alkylalkoxy Silane. Silane sealers gave better performance than did siloxane sealers and water-based sealers performed better than did solvent based sealers (8). Other state agencies have also completed research comparing performance of sealers, including Kentucky Transportation Cabinet, Alabama Department of Transportation, and Oregon Department of Transportation.

While the Wisconsin and Colorado studies were laboratory testing programs, Minnesota constructed test sections on an in-service bridge to evaluate 12 deck crack sealant products. They found that material properties like tensile elongation did not correlate well with sealant performance. The study used the NCAT permeameter, coring and petrographic evaluation to rate each product after each winter of

service. The predominate failure mode was detachment from the crack face, not within the sealant. Only four percent of the sealants were judged to be effective after two winters. 42 percent were partially effective after 3 winters. Another comment from the study that has bearing with regard to mobility impacts is that flood sealing requires significantly less time to apply but uses more sealant product (9).

Michigan reported on two types of epoxy flood coats for preventive maintenance treatment of bridge decks: a one-coat penetrating healer sealer flood coat and a two-coat epoxy overlay. The overlay provides a more aesthetic driving surface, requires that the surface be prepared to the International Concrete Repair Institutes (ICRI), Concrete Surface Profile 7, and has a minimum construction time of 3 days. The penetrating healer sealer seals cracks in the bridge deck but does not provide a wearing surface, requires a less rigorous surface preparation, and has a one-day construction operation (10).

Sealant effectiveness was also addressed by Rahim, Jansen, and Abo-Shadi in their report to Caltrans. Their study focused on HMWMs, to be applied to a new deck at 3 to 6 months and to be repeated every 4 to 5 years. Alberta's Ministry of Infrastructure and Transportation applies HMWMs every 4 years. Oman recommended that Minnesota reduce its application cycle from 5 years based on the 2014 report.

A study by Ley, et al. (11) for Oklahoma Department of Transportation evaluated the expected life of silane water repellant treatments on bridge decks using a sample of 60 bridges that had silane treatments aged between 5 and 20 years. They found that after 12 years, 100% of the silane applications were effective. That level dropped to 68% by 15 years and to 16% between 17 and 20 years.

Epoxy sealers, methacrylate sealers, and silane sealers are the most common deck sealers reported for either current common practice or new/experimental use in the Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments (3).

Notes on Michigan Practices

Based on the results of Survey 2 (see Chapter 5 for details), cyclic application of healer sealer is conducted by Superior region on a 5-year cycle. Superior, Grand and University regions all apply the initial healer sealer at 5 years. Bay and Grand regions apply an epoxy overlay at 15 years. Metro region applies a healer sealer in year 10, followed by epoxy overlays at years 20 and 30. University region applies epoxy overlays at years 20, 50 and 75. Superior region applies epoxy overlays at years 38 and 68.

For sealing localized cracking and as a penetrating healer sealer on bridge decks, Michigan DOT uses a two component epoxy based healer sealer. When used as a healer sealer, the material must be solvent-free and moisture insensitive. Aggregate for the healer sealer application must be angular and consist of natural silica sand, basalt or other nonfriable aggregate and meet the aggregate moisture content and gradation requirements in 12SP-710B-04. As of 9-12-2019, five products were approved for this activity: E-Chem (EP100), Euclid Chemical (Dural 335 or Dural 50 LM), Poly-Carb (Mark 127), Sika (Sikadur 55 SLV), and Unitex (Pro-Poxy 40 LV/ LM). The most current list of approved products should be consulted before selecting a product.

References

1. Morse, Kelly L, “*Effectiveness of Concrete Deck Sealers and Laminates for Chloride Protection of New and In Situ Reinforced Bridge Decks in Illinois*”, Illinois Department of Transportation, Bureau of Materials and Physical Research, Springfield, Illinois, October 2009.
2. Rahim, A, Jansen, D., and Abo-Shadi, N, “*Concrete Bridge Deck Crack Sealing: An Overview of Research*”, California Department of Transportation Report #F051R345, Sacramento, California, May 2006.
3. Krauss, Paul D., Lawler, John S., and Steiner, Kimberly A., “*Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments*”, National Cooperative Highway Research Program Project 20-07, Task 234, Transportation Research Board, Washington, D.C., May 2009.
4. Liang, Yu-chang, Gallaher, Benjamin, and Xi, Yuping, “*Evaluation of Bridge Deck Sealers*”, Colorado Department of Transportation, Applied Research and Innovation Branch, Report No. CDOT-2014-6, Denver, Colorado, June 2014.
5. Pincheira, Jose A. and Dorshorst, Melissa A., “*Evaluation of Concrete Deck and Crack Sealers*”, Wisconsin Highway Research Program, Report #0092-03-09, Madison, Wisconsin, December 2005.
6. Xi, Yunping, Li, Linfei and Railsback, Renee, “*Evaluation of Different Types of Waterproofing Membranes (Asphaltic and Non-Asphaltic) as Cost Effective Bridge Deck Barriers in Reducing Corrosive Chloride Effects*”, University of Colorado, Boulder, Colorado, Report FHWA-HRT-15-078, June 2018.
7. Liang, Yu-chang, Gallaher, Benjamin, and Zi, Yunping, “*Evaluation of Bridge Deck Sealers*”, University of Colorado, Boulder, Colorado, Report CDOT-2014-6, June 2016.
8. Mostafa, Karim and Sanders, David, “*Improving the Long-Term Performance of Concrete Bridge Decks Using Deck and Crack Sealers*”, University of Nevada, Reno, Nevada, Report CCEER 18-02, June 2018.
9. Oman, Matthew S., “*Concrete Bridge Deck Crack Sealant Evaluation and Implementation*”, Office of Transportation System Management, Report 2014-34, St. Paul, Minnesota, September 2014.
10. DeRuyver, Jason, “*Michigan’s Experience with Flood Coats*”, Concrete Bridge Views, Issue 75, March/April 2014, Federal Highway Administration and the National Concrete Bridge Council joint publication. Available on TSP2 website.
11. Ley, M. Tyler, Moradilo, Mehdi Khanzadeh, “*Expected Life of Silane Water Repellant Treatments on Bridge Decks, Phase 2*”, Oklahoma State University, Stillwater, Oklahoma, Report FHWA-OK-15-05, October 2015.

Bridge Deck Overlays

Deck overlays are applied to protect the bridge decks from deterioration due to water and corrosive chemicals reaching the reinforcing steel. An overlay should prevent the infiltration of water and chemicals into the underlying deck and supporting structural elements. They must be durable, cost effective, and provide adequate frictional resistance. The most common types include Portland cement concrete overlays, low slump concrete overlays, high performance concrete overlays, asphalt concrete overlays with or without waterproofing membranes, polymer overlays, and latex modified concrete. Fly ash modified concrete and silica-fume modified concrete are also used for overlays on bridge decks. Of

these, the asphalt overlay with waterproofing membrane and polymer concrete overlays are most often used. Replacement of asphalt concrete overlays was the dominant treatment for steel bridge decks and timber bridge decks (1).

A summary of bridge deck overlay treatments is included in Table 2.3. Note that additional information about epoxy overlays is included in the preceding section on deck crack repair and deck sealing.

| Treatment | Notes | Time |
|------------------------------------|--|--|
| Epoxy Overlay | Michigan uses a two-layer epoxy overlay. Polymer overlay | 3 day activity |
| HMA with waterproofing membrane | Requires primer, then application of membrane; up to 2 days before asphalt overlay is applied. | |
| HMA without waterproofing membrane | Standard asphalt paving operation. | |
| Concrete overlay | May be modified with latex, fly ash, or silica fume. | Regular concrete- 7-day cure Latex and silica fume modified concrete- 56 hours Very Early Strength Latex Modified Concrete can be placed and opened to traffic in 8-hours. |

Table 2:3 Bridge Deck Overlay Types

Overlays may also be used to remedy cases with minor deck delaminations or inadequate depth of cover over reinforcement. One design consideration is the added dead load associated with the overlay. Thin overlays of latex or polymer concrete may be required when limited additional dead load can be accommodated. For example, Washington State Department of Transportation normally uses a 1.5-inch thick modified concrete overlay as its primary overlay type but uses 3/8-inch thin polymer overlays when dead load limits the weight of the overlay (2). A report on commonly used bridge deck overlays in Virginia (3) indicated that the most commonly used are latex-modified concrete, epoxy concrete, silica fume concrete, very-early-strength latex-modified concrete, and hot-mix asphalt with a water-resistant membrane. Virginia is evaluating the performance of these overlays in continuing research. Hunsucker, et al. (4) identified latex modified concrete, micro silica concrete, superplasticized dense concrete, fly-ash modified concrete and polymer modified concrete as acceptable choices for bridge deck overlays in Kentucky. In addition to considering the depth of chloride contamination, the degree of deck damage will influence the performance of the overlay. The higher the pre-overlay deck damage, the worse the performance of the overlay. In NCHRP 20-07, Task 234, California limited deck damage for a treatment other than deck replacement to less than 20%, while 50% was the threshold for Connecticut, Massachusetts and Kansas (1). The percentage of distress includes patches, spalls and delaminations. The durability of the overlay, particularly to snow plow damage, and to freeze thaw damage must be considered.

Other overlay considerations include traffic constraints on construction closures, previous deck overlays and repairs, clearance restrictions and needed drainage and slope corrections, costs and service life, and contractor and DOT experience (1). Speed of construction and time to opening to traffic vary

significantly. Conventional concrete overlays include high performance concrete, latex modified concrete, low-slump concrete and fiber-reinforced concrete. Construction times vary. High performance concrete has had freeze thaw durability issues. High performance concrete has the same material components as regular concrete but is proportioned to provide lower permeability and reduced cracking. Caltrans indicates that a standard Portland cement concrete overlay requires a 7-day curing period before being opened to traffic (5). Both latex modified concrete and silica fume concrete can be placed and cured within 56 hours.

Very Early Strength Latex Modified Concrete (VESLMC) can be placed and opened to traffic in 8 hours. A very early strength polymer modified concrete is constructed and cured in a similar manner to VESLMC, but the polymer is in the cement instead of being added as a liquid (6).

Overlay performance, both in bonding to the underlying deck and in preventing chloride damage is highly dependent on deck preparations. Placement of an overlay does not stop the chloride ions already in the concrete deck from reaching the steel reinforcement. If there are significant chlorides in the existing deck, it is recommended to remove much of the chloride-contaminated concrete. Sprinkel et al. (7) recommended removal of all concrete with a chloride content over 1.0 lb./yd³. One district of the Virginia Department of Transportation removes about 1.75 inches of surface concrete by milling, and an additional 0.5 inches by hydro-demolition prior to placing an overlay (8). If critical chloride concentrations exist to the depth of the second layer of reinforcement and steel quality is degraded, deck replacement will be required.

The Virginia Transportation Research Council, in a Phase 1 report on “Performance of Bridge Deck Overlays in Virginia” (8), outlined the pros and cons of overlays and recommended uses of various bridge deck overlays.

- Thin Polymer Overlays are formulated to cure rapidly. They require less labor and specialized equipment than a rigid overlay. Since they are applied in small thicknesses of generally 0.25 to 0.75 inch, they do not add significant dead load. They will not improve cross-section geometry, drainage patterns or ride quality. Epoxy polymer overlays perform well if the bridge deck is in good condition, is free of working cracks, and has chloride contamination levels of no more than 1 to 2 lb./yd³ of concrete. The polymer resin can be applied by spray, roller, brush, or squeegee, after which a gap-graded aggregate is broadcast over the layer of resin. This process is repeated for a multiple layer overlay. In addition to this form of polymer overlay, slurry and premixed polymer concrete are available. The most commonly used binders for polymer overlays are epoxy, polyester styrene, and methacrylate. Quality depends on existing deck quality, repairs being made with a compatible polymer patching material, the deck being sufficiently clean and dry throughout the curing process. Service life reported by Virginia DOT depended on traffic volumes; 10 years for ADTs greater than 50,000 and 25 years for ADTs less than 5,000.
- *Use of a patching material recommended by the polymer concrete manufacturer can save significant time and cost. It may be possible to eliminate the cost of a second traffic control as well as reducing the time to let patches cure, dry and outgas. One method of implementing this concept would be through Value Engineering proposals from the contractor.*
- Rigid Overlays reduce chloride and moisture infiltration, improve ride quality, and improve skid resistance. Bonded overlays become structural components and may add structural capacity to

the deck. Portland cement concrete, latex modified concrete, silica fume concrete, and low slump dense concrete are common types of rigid overlays. The construction process consists of scarifying and removing unsound concrete by milling or hydro-demolition, removing concrete dust by grit or shot blasting, saturating the milled deck with water for 12 hours, placing the overlay on saturated surface dry deck and properly curing for time appropriate for the cement used. Rigid overlays are generally placed on decks with a higher level of deterioration than the thin polymer overlays. Overlay service lives vary with environmental exposure and salt usage. High performance concrete, which is composed of the same materials as standard concrete but are proportioned for high strength or lower permeability, may be used for bridge overlays. High performance concrete overlays had a service life of 16 to 29 years, while latex modified overlays had mean service life range of 14 to 29 years.

- Latex-Modified Concrete (LMC) is a Portland cement concrete in which a portion of the mix water is replaced by an admixture containing styrene butadiene latex particles suspended in water. LMC overlays have very low permeability, low chloride ingress, adequate compressive strength and high flexural strength. Construction of LMC overlays requires specialized equipment, contractor experience and is sensitive to weather conditions. An LMC overlay typically requires a deck closure of 1 to 2 days.
- *Very Early Strength Latex Modified Concrete (VESLMC) uses a specially blended Rapid Set cement in LMC to allow opening to traffic in as little as 3 hours. These overlays are susceptible to construction errors. Shrinkage cracking is the most common issue and the following measures are recommended to reduce the risk:*
 - *Use cement with the lowest early strength possible,*
 - *Use a low amount of very-early-strength cement,*
 - *Maintain a low hydration temperature,*
 - *Use the minimum necessary cement paste volume, and*
 - *Prevent restraint to promote free shrinkage. Moist curing is essential to reduce the risk of shrinkage cracking.*
- Silica Fume (SF) Concrete contains an admixture of silica fume as a substitute for a portion of the cement. Due to the small particle size of SF, it is effective in reducing permeability and ingress of water and chlorides. It bonds well with the underlying deck and is freeze-thaw durable. It is easy to install, requiring no special equipment or extensive contractor experience. It has a greater need for water for hydration, and cracking may occur if the curing process is not managed well. A shrinkage reducing admixture may reduce the tendency to crack.
- An Asphalt Concrete Overlay with a waterproof membrane consists of a layer of hot mixed asphalt concrete over an impermeable membrane. The membrane may be either pre-formed or constructed-in-place. Prior to placing the asphalt overlay, concrete patches should be cured for at least 14 days. The deck surface must be dry. A primer should be applied and allowed to dry to tack-free condition. The pre-formed membrane should be rolled onto the surface and edges should be sealed with a polyurethane sealer or a mastic. Within 2 days of installation of the membrane, the hot mixed asphalt overlay is applied. The membrane, in addition to being impermeable to water, must also tolerate deck surface irregularities, bond well with the deck, be capable of carrying traffic before application of the riding surface, and be able to withstand a

wide range of temperatures. A hot mixed asphalt overlay with an impermeable membrane is easy and quick to install, low cost, and can bridge most moving concrete cracks. One of their biggest disadvantages is that they make it difficult to inspect the condition of the underlying concrete deck and the membrane. The membrane may be difficult to remove at the end of the service life. The predicted service life had a mean range of 12 to 19 years (8).

Additional evaluations of thin polymer overlays for bridge decks were conducted by Tabatabai, et al. (2) and Dahlberg and Phares (9). The first study, from Wisconsin, found that the overlay system with an epoxy resin and flint rock aggregate provided the best overall performance, but that the multi-lift polymer overlay systems delaminated from the concrete surface for all nine test specimens. The second study looked at field performance of two overlaid bridge decks over a two-year period. They found localized failure areas that they attributed to poor deck preparation, improper polymer mixing and/or snowplow impact.

Causes of overlay failures have included improper surface preparation, surface moisture, out-of-range concrete temperature, deck patches that have not adequately cured, unsound concrete deck surface, and pre-existing corrosion deterioration. Specifications should address surface preparation requirements, aggregate quality (hardness, shape, dryness, cleanliness), thermal compatibility between the overlay materials and the existing concrete deck, quality control procedures and tests, and the experience of crews (10).

Notes on Michigan Practices

Survey 2 (see Chapter 5 for details) revealed that a variety of overlays are used on bridge decks in Michigan. The Metro region plans on two epoxy overlays, at years 20 and 30. University region uses epoxy overlays in years 20, 30 and 50, and applies a deep concrete overlay in year 40. Grand and Bay regions apply an epoxy overlay in year 15, followed by a deep concrete overlay in year 30, and an asphalt overlay without water proofing membrane at year 75 (with water proofing membrane at year 65 for Bay). North region applies an epoxy overlay in year 2 and an asphalt overlay with water proofing membrane at year 70. The most cyclic approach is reported by Superior region. Beginning in year 10, an epoxy overlay is applied about every 10 years through year 60. At 75 years, an asphalt overlay with water proofing membrane is applied.

Special provision 12SP-712B-05 contains the details related to thin epoxy polymer bridge deck overlays. The two-part epoxy system must be solvent free, moisture insensitive, 100 percent solids and low-modulus. Eight products are approved: BASF (MasterSeal 350), E-Bond (526 Lo-Mod), E-Chem (EP50 Euclid Chemical (Flexolith, Flexolith Summer Grade, Flexolith HD), Poly-Carb (Flexogrid Mark 163, Flexogrid Mark 154), Sika (Sikadur 22-Lo Mod) and Transpo (T-48 Chip Seal), and Unitex (Propoxy Type III DOT). Aggregate must meet the gradation, hardness requirements, and moisture content specified in the special provision. Five approved aggregate suppliers are listed. The average cure times for each of the two courses depend on the average temperature of the deck and the component materials and vary between 1 and 2 hours per lift for temperatures in the range of 60°F to 85+° F. The most recent revision of the special provision should be consulted before selecting a product.

Information on concrete overlays for bridge decks can be found in Table 703-2. For silica fume modified concrete, dry densified silica fume is required, along with virgin polypropylene collated fibers

and air entraining admixture. If latex modified concrete is used, water in the latex admixture and any additional water must control slump to 3 to 5 inches. Details for the mixture designs are located in Table 703.2 (updated 6-25-2018).

References:

1. Krauss, Paul D., Lawler, John S., and Steiner, Kimberly A., “*Guidelines for Selection of Bridge Deck Overlays, Sealers and Treatments*”, National Cooperative Highway Research Program Project 20-07, Task 234, Transportation Research Board, Washington, D.C., May 2009.
2. Tabatabai, Habib, Sobolev, Konstantin, Ghorbanpoor, Al, Nabizadeh, Azam, Lee, Chin-Wei, and Lind, Matthias, “*Evaluation of Thin Polymer Overlays for Bridge Decks*”, Report No. 0092-12-06, Wisconsin Department of Transportation, Madison, Wisconsin, July 2016.
3. Balakumaran, Soundar S, Weyers, Richard E, and Brown, Michael C, “*Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays*”, Virginia Research Council, Richmond, VA, Report FHWA/VTRC 17-R17, May 2017.
4. Hunsucker, David, Ashurst, Kean, Jr., Rister, Brad, Allen, David, and Grady, Eileen, “*Longer Lasting Bridge Deck Overlays*”, University of Kentucky, Lexington, Lexington, KY, Report KTC.RR.2018.6, April 2018.
5. “*Overlays on Existing Bridge Decks*”, Memo to Designers 8-5, Caltrans, Sacramento, California, May 1996.
6. Sprinkel, Michael M., “*LMC Overlays for Bridge Deck Preservation*”, Virginia Center for Transportation Innovation and Research, presented at the Southeast Bridge Preservation Partnership meeting and available on the TSP2 website, Raleigh, NC, April 13-15, 2011.
7. Sprinkel, M. M. and Weyers, R. E., “*Rapid Concrete Bridge Deck Protection, Repair and Rehabilitation*”, Strategic Highway Research Program S-344, National Research Council, Washington, D.C., 1993.
8. Balakumaran, Soundar, Weyers, Richard, and Brown, Michael C, “*Performance of Bridge Deck Overlays in Virginia: Phase I: State of Overlays*”, Final Report VTRC 17-R17, Virginia Transportation Research Council, Charlottesville, Virginia, May 2017.
9. Dahlberg, Justin M., and Phares, Brent, “*Polymer Concrete Overlay Evaluation*”, Iowa State University, Ames, Iowa, InTrans Project 13-463, June 2016.
10. Fowler, D. W. and Whitney, D. W., “*Long-Term Performance of Polymer Concrete for Bridge Decks*”, National Cooperative Highway Research Program Synthesis 423. Transportation Research Board, Washington, D.C., 2012.

Concrete Deck (and other concrete) Removal

Partial depth removal may be required due to delamination or other defects extending to the depth of the top layer of reinforcement. Full depth removal is required when the deck condition has deteriorated too extensively, or corrosion damage extends well into the slab thickness. Since deck removal has been a labor-intensive operation, Phares, et al. (1) studied methods for removing concrete decks from bridge girders. They describe the following removal techniques:

- Sawing,
- Breaking,
- Hydrodemolition,

- Drilling,
- Splitting,
- Crushing,
- Blasting
- Peeling.

Sawing, in combination with breaking (usually with jackhammers) is the traditional removal method. Hydrodemolition is suitable for both partial and full depth concrete removal but treating the resulting wastewater and concrete is expensive. Splitting can be either mechanical or chemical but did not sufficiently break the reinforced concrete. Crushing is difficult to use over beams and would require extensive hand work over girders. Blasting is more suitable for eliminating the whole bridge rather than the deck. Peeling applies vertical forces on the deck to break the concrete free from the girders. Few field reports are available on this method. Drilling is used in concert with other techniques, such as chemical splitting or blasting.

Hydrodemolition can be used as a “fast track operation in which the “robot” selectively applies a combination of water flow and pressure to remove deteriorated concrete to specified depths across the full deck surface in a single pass” (2).

Work by Phares, et al. (3) looked at techniques to accelerate the construction of bridge deck overlays. One of their conclusions was that significant construction time could be saved by limiting concrete removal as follows: if unsound concrete exists only above half the diameter of the top layer of reinforcing steel bar, all concrete should be removed to half the diameter of the reinforcing steel; if unsound concrete exists below half the diameter of the reinforcing steel bar, all the unsound concrete should be removed to its extent, but no additional sound concrete should be removed. The authors also recommended consideration of substitute materials for class HPC-O and O concrete mixes: specifically, CTS Rapid Set low-P cement mixes, 4x4 concrete mix, polyester polymer concrete and very early strength latex modified concrete. These materials would reduce curing time.

The Ohio Department of Transportation has explored use of hydrodemolition to remove damaged concrete from parapet walls. A report by Miller, et al. (4) recommended hydrodemolition because it does not damage sound concrete. They recommend use of a protectant coating, polyurea, to coat the removal areas following hydrodemolition.

References

1. Phares, Brent M., Shane, Jennifer, Dahlberg, Justin, and Dang, Hongtao, “*Methods for Removing Concrete Decks from Bridge Girders*”, Iowa State University, Ames, Iowa, Report WBS-25-1121-0003-134, August 2014.
2. Martens, Patrick, “*Total Surface Selective Removal of Concrete Utilizing Hydrodemolition*”, Missouri Department of Transportation, Jefferson City, MO, Report CMR 15-001, July 2014.
3. Phares, Brent, Hosteng, Travis, Greimann, Lowell, and Pakhale, Anmol, “*Investigation of Techniques for Accelerating the Construction of Bridge Deck Overlays*”, Iowa State University, Ames, Iowa, Report InTrans Project 14-500, April 2016.

4. Miller, Richard, Delatte, Norbert, and Mullins, Sarah, “*Evaluation of Maintenance Procedures for Bridge Spalling on Parapet Walls*”, University of Cincinnati, Cincinnati, OH, Report FHWA/OH-2017-15, March 2013.

Spot and Area Coating Repairs

According to NCHRP Project 14-30, there are about 170,000 steel bridges in the United States that depend on coatings to resist corrosion. In addition to these steel bridges, there are many more bridges with concrete decks and piers, but steel girders, which are also subjected to corrosive fluids through bridge joint leakage or salt spray. The exposure environment includes UV radiation, moisture, oxygen, and deicing chemicals. Marine environments and industrial exposure can also accelerate corrosion.

There are four maintenance painting options ranging from spot painting to zone painting to overcoating, and finally to coating removal and replacement. Table 2.4 shows the four levels of maintenance painting, their estimated unit costs, and estimated service lives. As you move from spot painting to each of the other painting options, the size of the area to be treated and the level of surface preparation increase. Many factors influence which option is selected, including, but not limited to, overall condition of the intact coating, extent of deterioration of the distressed coating, amount and criticality of structural member corrosion, surface contaminants, work site environmental factors, bridge type and importance, traffic management issues and painting budget (Hopwood et al., 2018).

Not all areas of the bridge experience the same level of exposure. For example, corrosion is likely to occur at beam ends and bearings under joints. It may also occur where salt-contaminated aerosols are kicked up by traffic. The result is local areas of coating failure that can be corrected if treated with spot coating before serious corrosion occurs.

| Coating Levels | Expected Unit Costs | Expected Service Life | Comments |
|-----------------------|---|------------------------------|---|
| Spot Coating | Most expensive unit cost, but only affecting 10 to 25 percent of existing coating | 7 to 15 years | Expected life 5 to 7 years in highly stressed locations |
| Zone Coating | More expensive than either overcoating or remove and replace | 10-20 years | Mild to moderate climate |
| Overcoating | ½ to 2/3 cost of remove and replace | 10-15 years | Mild to moderate climate |
| Remove and Replace | \$10/sq. ft to \$30/sq. ft. | 20-30 years | Low cost is rural deck/girder bridge |

Table 2:4 Coating Levels and Their Expected Costs and Service Lives

The predominant varieties of coatings used for spot coating include waterborne acrylics, alkyds, epoxies, polyurethanes, and zinc-rich coatings. The zinc-rich coatings require profiled steel, a level of surface preparation that is not common for spot coating. The quality of materials and workmanship are important to spot coating performance, but surface preparation and the severity of the local environment of the repair are most important. All the coating types described below can be used on marginally prepared surfaces, or surfaces prepared using commonly available hand tools.

Acrylics are one component coatings with low levels of Volatile Organic Compounds (VOC). They have low temperature and humidity restrictions and cannot be used in contact with salt contaminated steel. When used as a top coat, they are commonly used with other coating types. They may also be used as a primer. Similarly, conventional alkyds can be used as primer, intermediate or finish coat, in combination with a variety of existing coatings. They tend to cure slowly and are unsuitable for immersion or in areas likely to be exposed to chemicals or solvents. Calcium Sulfonate alkyds are also unsuitable for immersion or on salt contaminated steel without removal and replacement of existing coatings. They are very slow curing.

Epoxyes are used as sealers, primers, and intermediate coats due to their excellent resistance to corrosion, chemicals, and abrasion. They are slow curing and have limited pot life. Epoxy mastics have similar resistance to corrosion and chemicals and can be installed in multiple layers. They have slower drying time than regular epoxyes.

Two-component polyurethanes have excellent abrasion and chemical resistance and are fast curing. Some two-component polyurethanes are used as finish coats. They have limited pot life and are not suitable for immersion as a topcoat. Moisture-cure polyurethanes are one-component systems that often serve as a primer or intermediate coat. The curing is dependent on the humidity level. Moisture-cure polyurethanes have excellent chemical resistance, good corrosion resistance and can be applied to surfaces that will be immersed.

In general, coatings should not be applied in rain, wind (more than 25 miles per hour), snow, fog, or mist or when the surface to be coated is less than 5 degrees F above the dew point. A minimum temperature of 35°F to 40°F and a maximum of 120°F to 125°F are common. A maximum relative humidity of 85 percent also applies to most products. Each product supplies additional guidance including recommended surface preparation, spreading rates, drying schedule, storage information, tinting, application conditions, and safety precautions.

Traffic control may be required for spot painting activities depending on the locations to be coated. Proper tie offs are required for workers over six feet off the ground. Waste containment may be required if lead paint is present at the structure.

Surface preparation for spot coating consists of solvent cleaning, hand tool cleaning, washing and soluble salt treatment, and power tool cleaning. Solvent cleaning removes tars, oil or grease from the surfaces. Hand tool cleaning generally consists of removal of loose paint, pack rust and loose rust and debris using scrapers, hammers, chisels, wire brushes, and abrasives. For areas with levels of soluble salts above agency thresholds, pressure washing at pressures of 2,500 to 5,000 psi are used. Washing troughs may be needed to capture the run-off. Power tool cleaning for spot cleaning is intended to remove rust, paint, scale, and foreign material using reciprocating sanders, orbital sanders, grinders, and reciprocating impact tools. The weight of the power tools has significant impact on worker production. NCHRP 14-30 found that a worker could clean for about 8 hours with an 8-pound power tool but increasing the weight of the tool by 1 pound, decreased their ability to work to 4 hours (Hopwood, et al, 2018).

Spot painting the prepared surface is accomplished using brushes, rollers, daubers, mitts, and sprayers. All except spraying can be done by relatively unskilled workers with limited impact on the environment.

Spot painting should be inspected for adequate coating thickness and any areas with blistering, delamination or other irregularities should be corrected.

The Virginia Department of Transportation has an on-going research project evaluating the use of a laser ablation coating removal (LACR) system to improve the efficiency of coating removals in preparation for re-painting. This technology is being evaluated based on its effectiveness in preparing steel surfaces, the impact on environmental and health safety, and the effectiveness of the repainted coatings. Preliminary indications are that the production rates are low and application to large surface areas such as full superstructures may be cost prohibitive (3).

Agencies face conflicting performance reports regarding coating products and systems. For example, Khan (4) reported that in comparisons of two 2-coat paint systems against the standard three-coat system used by Maryland State Highway Administration, the three-coat system was the best performing system. Research by Toubia and Emami (5) tested two-coat systems consisting of zinc-rich primer and polysiloxane topcoat subjected to three different temperature environments. They found comparable performance of the two coat systems to the three-coat system regardless of the environment. The two-coat system has quicker set time and better adhesive strength. Bob Parker (6) presented use of fluoroethylene vinyl ether (FEVE) technology as an effective topcoat for a three-coat system.

Notes on Michigan Practices

Most regions in Michigan use a combination of zone painting and complete painting to maintain coating systems. Bay and Grand regions coat concrete beams, concrete barrier and deck fascia in year 15. Bay region applies coating to concrete substructure in year 20 and paints the complete structure in year 35. Grand and North regions utilize zone painting of steel structural elements at year 20, and delay complete painting until years 55 and 40, respectively. Metro region reported spot painting of steel structural elements at year 20 and complete painting at year 50. Superior region uses zone painting at years 20, 30 and 60; with complete painting at year 40. More details on Michigan bridge activities can be found in Chapter 5.

Michigan Special Provision 12TM710-A320-02 provides details on surface coatings for concrete. This special provision includes a list of 15 approved suppliers and products. All are acrylic based and intended for use on retaining walls, noise walls, barriers, fascias, cheekwalls, piers, and substructure locations. Surface preparation is stressed in the special provision to insure that the surface is free of dirt, form release agents, oil, grease, curing compounds, loose material and other contaminants. Consult the most recent version of the special provision prior to selection of a product.

Michigan Special Provision 12SM710(A010) contains details for spray-applied penetrating silane sealer for bridge barriers and deck fascias. Nine products are approved in the special provision: ChemMasters (Aquanil[™] Plus 100), Euclid Chemical (Baracade Silane 100C), Vexcon (Certi-Vex Penseal 244 100%), BASF (MasterProtect H 1000), Pecora (KlereSeal 9100-S), Evonik (Protectosil BH-N), Sika (Sikagard 705L), Advanced Chemical (SIL-ACT[™] ATS-100), and Dow Corning (Xiameter OFS-6403 Silane). Consult the most recent version of the special provision prior to selection of a product.

References

1. Hopwood, Theodore II, Palle, Sudhir, Meade, Bobby, Younce, Rick, Wells, Danny, and Goff, Christopher, “*Spot Painting to Extend Highway Bridge Coating Life: Volume 1, Guidance*”, National Cooperative Highway Research Program Web Document 251, NCHRP project 14-30, National Academies of Sciences, Washington, D.C., January 2018.
2. Hopwood, Theodore II, Palle, Sudhir, Meade, Bobby, Younce, Rick, Wells, Danny, and Goff, Christopher, “*Spot Painting to Extend Highway Bridge Coating Life: Volume 2, Research Overview*”, National Cooperative Highway Research Program Web Document 251, NCHRP project 14-30, National Academies of Sciences, Washington, D.C., January 2018.
3. “*Implementation of Coating Removal Technique for Steel Components on VDOT Bridges*”, project of Virginia Transportation Research Council, Charlottesville, VA, Principal Investigators: James Fitz-Gerald, Sean Agnew, Stephen Sharp and James Gillespie. Expected Completion date: 12-31-2018.
4. Khan, Shameem, “*Bridge Coating Performance: Two-Coat vs Three-Coat Systems*”, Journal of Protective Coatings and Linings, Steel Structures Painting Council, Volume 31, Issue 5, pp 31-40, May 2014.
5. Toubia, Elias and Emami, Samin, “*Experimental Evaluation of Structural Steel Coating Systems*”, Journal of Materials in Civil Engineering, American Society of Civil Engineers, Reston, VA, Volume 28, Issue 12, Dec. 2016.
6. Parker, Bob, “*FEVE Technology for Higher Performance Coating Systems on Bridges*”, Journal of Protective Coatings and Linings, Steel Structures Painting Council, Volume 32, Issue 1, pp 38-46, January 2015.

Deck and Superstructure Washing

Two studies were completed in 2013 dealing with agency practices and the effectiveness of bridge washing activities.

A synthesis of practices for washing and cleaning concrete bridge decks and substructure bridge seats was prepared by Burgdorfer, et al. (1) for Washington State Department of Transportation. It was based on two surveys: a nationwide survey that identified state practices and the frequency of bridge washing, and a follow-up survey with both states that wash bridge decks and those who do not. The emphasis of the study was on bridge components known to have high maintenance costs: decks, expansion joints, substructure seats and bearings. The nationwide survey found an almost even split between agencies who never wash and those that wash either every year or every other year. Washing programs were most common in agencies in the Northeast, followed by the Midwest.

In the follow-up survey, several of the agencies who do not have bridge washing programs cited environmental requirements to collect both debris and wash-water or lack of funds to maintain the program.

A 1995 FHWA/ NHI Course titled “LRFD Design of Highway Bridges” states that bearings and expansion joints are likely to have a shorter life than the bridge as a whole. Bearings are frequently located in areas likely to accumulate debris and moisture. Joints also have issues with debris accumulation, and troughs under joints, intended to drain water away from the underlying structure, also collect debris. (2).

The literature review conducted as part of this study found little information tying bridge washing to bridge performance. A synthesis report titled “Bridge Deck Joint Performance (3)” concluded that preventive maintenance extends the service life of expansion joints. That preventive maintenance included washing decks, clearing drains, removing debris and minor repairs.

The 2013 report by Alland, et al. (4) for Pennsylvania Department of Transportation evaluated the effectiveness of bridge cleaning for steel structures. They found that beams within 23 feet of the road surface contained high concentrations of salt on the bottom flange and should be included in bridge washing. They also recommended extra washing of damaged expansion joints to minimize damage below the joints. They also found that washing was ineffective on bridges where the coating has failed due to high concentrations of salt in pitted areas.

The study found that a fully functioning pressure washer is necessary to remove a significant amount of salts and that best cleaning occurs when the angle of the water stream to the area being cleaned approaches 90 degrees.

Notes on Michigan Practices

Only Superior region reported a cyclic pattern of bridge deck cleaning and washing. They conduct this work every other year throughout the life of the bridge. More details on results of Survey 2 can be found in Chapter 5.

References:

1. Burgdorfer, Ryan; Berman, Jeffrey; and Roeder, Charles; “Standard Practice for Washing and Cleaning Concrete Bridge Decks and Substructure Bridge Seats Including Bridge Bearings and Expansion Joints to Prevent Structural Deterioration;” Washington State Department of Transportation, Olympia, WA; Report WA-RD 811.2; December 2013.
2. “LRFD Design of Highway Bridges;” Federal Highway Administration and the National Highway Institute; Washington, DC; Course 13061, Chapter 14; 1995.
3. National Cooperative Highway Research Program; “Bridge Deck Joint Performance;” Synthesis 319, Transportation Research Board, Washington, DC; 2003.
4. Alland, Kevin; Vandenbossche, Julie M.; Vidic, Radisav; and Ma, Xiao; “Evaluation of Bridge Cleaning Methods on Steel Structures;” Pennsylvania Department of Transportation, Harrisburg, PA; FHWA-PA-2013-007-PIT WO 2; December 31, 2013.

Bearing Replacement

Replacement of bearings is typically done by jacking to raise all beams at a headstock sufficiently to free the bearing for resetting or replacement. Tight control is required during the jacking operation to avoid damaging the structure and to restore the original bearing reactions. This is difficult, especially when uneven thicknesses of epoxy are present above or below the bearings. This operation is normally conducted in an overnight closure, but traffic can be adversely impacted if issues develop during the jacking and replacement process.

An alternate approach is reported by Hart, et al. (1). In this approach a single bearing is replaced or reset. Hydraulic jacks placed close to the bearing apply a slight (less than 1 millimeter) upward displacement. The existing bearing is removed or reset while the load is transferred to the hydraulic

jacks. The new bearing is placed on a permanent flat jack, which is inflated with epoxy to restore the previous load as soon as the epoxy hardens. The hydraulic jacks are then removed. Hart, et al. (1) recommend this method for major roads, very wide bridges, bearings with variable thicknesses of epoxy, or where only isolated bearings require replacement.

Notes on Michigan Practices

Only Bay region included bearing replacement at year 50 in their 75-year bridge action plan. For details on the results of the Michigan survey, see Chapter 5.

Reference:

Hart, J; Asl, A; and Fletcher, J; “*Bridge Bearing Replacement Using Flat Jacks*”, 10th Austroads Bridge Conference, Melbourne, Victoria, Australia, April 2014.

Deck Patching

Corrosion of the reinforcing steel resulting in its expansion, causes cracks in the concrete to initiate along the tops of the rebar lines. When the steel is exposed to water, oxygen and chlorides, it oxidizes and rusts, expanding to up to ten times its original volume. This expansion causes intense localized stress in the surrounding concrete, causing cracks to form. Similar distress may occur in carbonated concrete. The cracking accelerates the access of the chlorides and water to the reinforcing steel and distresses, including delamination potholes (spalls) occur in the concrete deck surface. These distresses pose not only a ride quality issue, but a safety issue. In addition, poor ride quality increases the vehicular impacts on the bridge. Repairs may be partial-depth, or in more severe cases, full-depth (1). Partial depth repairs may also be required due to initial slab defects such as improper consolidation or inadequate concrete cover over the reinforcing steel (2).

Unless all chloride-contaminated concrete is removed, deck patching will be a temporary repair. Chloride-contaminated concrete left in place will continue to cause corrosion of the underlying reinforcing steel, causing new cracking and delaminations. In addition, replacing a spalled area with chloride-free concrete can produce the so-called “halo effect” where damage occurs to the sound concrete surrounding the patched area.

Texas DOT classifies deck repairs, in addition to partial and full depth, according to the speed required to return the bridge to service. This is particularly true in urban environments, where a deck closure has huge adverse impacts on traffic. For depths exceeding 3 inches, four categories of deck repair are defined: 3 hours (ultra-rapid repair), 6 hours (rapid repair), 24 hours (using a specialty concrete that may be available from a Ready-Mix plant), and 2 to 4 days (using the same concrete mixes used to cast new bridge decks). Texas DOT’s experience has been that the more rapid the return to service requirement is, the more likely that the deck patch will have a shorter service life. They also note that very thin layers are poor performers due to debonding stresses between the thin patch and the underlying concrete. For this reason, Texas requires the contractor to excavate below the top layer of steel, allowing this steel to provide a mechanical tie and to guarantee a thicker deck repair (2).

Removal of deteriorated, damaged, and defective concrete is the first step in deck repair and must be done carefully and with appropriate tools to avoid cracking the underlying sound concrete. Both Texas and Ohio caution against using equipment too heavy for the applications. Saw cutting the perimeter of the repair area, without cutting reinforcing steel, will provide a limit for the concrete removal and avoid feathering of the repair material. Removal of concrete to a depth of $\frac{3}{4}$ inch (some variations in depth exist between states, but this depth is common) below the top layer of reinforcing steel is recommended ((3) and (2) contain examples).

All surfaces of the exposed reinforcement need to be cleaned to remove all loose mortar, rust, oil, and other contaminants. For small areas, this can be done with wire brushing, but for larger areas, abrasive blasting, followed by air blasting is preferred. If the reinforcing steel has had a section loss of 20% or greater, add additional reinforcement using lap splices. Texas DOT requires that the exposed and cleaned reinforcing steel be coated with an approved epoxy coating (2). All loose debris must be removed to insure a good bond. Indiana DOT requires resounding the deck to assure that all damaged concrete has been removed (4).

Depending on the patching material selected and agency practices, a bonding grout may be applied to all surfaces of the deck patch. The final patch must be placed prior to drying of the bonding agent. If no bonding agent is used and the patching material is cement-based, the area of the patch is wetted to achieve saturated surface-dry conditions. No puddles of water should be present. The patch material is thoroughly mixed, placed in the prepared patch area, vibrated to assure uniform density, and the surface is finished.

The deck repair areas should be moist cured for as long as is possible. Two layers of wet burlap, or one layer of wet burlap covered with plastic sheeting can provide moist curing. While 72 hours of curing time is ideal, Texas DOT has seen benefits from even a few hours of moist curing. The commentary states, “Because deck repairs must usually be performed quickly, Engineers and Contractors often select rapid methods even when they are not necessary. It is imperative that, when feasible, slower-hydrating materials and longer curing cycles be utilized. The faster the return to service, the shorter the anticipated service life of the patch” (2).

Full Depth Deck Patching

Texas DOT recommends inspecting the deck soffit at each location of an intended partial depth deck patch. If there is evidence of pattern cracking or widespread cracking with rust staining or efflorescence on the soffit, full depth patching should be undertaken (2). If the removal process for partial depth patches shows that unsound concrete is present to the level of the lower reinforcing steel, then full depth patching is warranted. Informal queries to North Carolina, Louisiana and Oregon resulted in non-specific guidelines for full depth patching. Oregon bases the determination on cracking and phosphorescence in the underside of the deck. North Carolina uses chloride content of 2.5 pounds per cubic yard. All three states depend on the expert judgement of their engineers. Full depth patching is also necessary to perform expansion joint replacement.

The steps for a full depth patch closely resemble those for partial depth patch with the exception that forms must be provided. Prior to this, damaged concrete is removed using equipment sized to minimize damage to sound concrete. Hydro-demolition is specified by Illinois DOT (5). TXDOT requires that

the area be squared or slightly undercut. They also suggest that full depth patches extend such that two sides are bearing on supporting elements (2).

The area of the patch is thoroughly cleaned using water blasting (TXDOT), sandblasting (Ohio), or an air-compressor with separators, traps or filters (Indiana). All reinforcing bars should be clean and additional bars added, with lap splices, when needed due to section loss to corrosion. Covering of reinforcing steel with an epoxy coating may be required.

Forms may be supported by hangers with adjustable bolts or by blocking from the beams below (5). All forms must be removed after curing of the full depth patch and prior to opening to traffic. Patching material placed within the prepared full depth patch area, is consolidated and the surface is finished. For cement-based patches, moist curing, with wet burlap or other materials is highly beneficial. If a curing compound is used instead of burlap, note that the curing compound must be removed prior to applying a waterproofing sealer (3).

Notes on Michigan Practices

Most regions included partial and full depth patching in their 75-year program of activities. Both Superior and North regions used a combination of partial and full depth patching over the 75-year period. Superior region plans on partial depth patching in years 11, 23, 33, 49, 65 and 70; full depth patching is anticipated in years 25, 41 and 59. Partial depth patching is planned for years 15, 20, 55 and 62 in North region. Full depth patching is scheduled for year 25. Bay region expects to conduct partial depth patching in year 15 and full depth patching in year 50. Grand, University and Metro regions included partial depth patching in years 15, 20 and 20, respectively. Details on the region activity lists can be found in Chapter 5.

Michigan generally uses a 7-sack Portland cement concrete for bridge deck surface repair, as specified in special provision 12CF706(A265). Emphasis is placed on adequate curing, with application of a curing compound followed by wet burlap and plastic sheeting that is to remain in place until just prior to opening to traffic. A compressive strength of 2,000 psi is required for opening to traffic, and a 7-day wet-during period is indicated. Insulating blankets may be required depending on weather conditions during the curing period.

A variety of prepackaged hydraulic fast set mortars are approved for use in Michigan. See section 703 on the qualified products list. Approved overlay mixtures are also used for deck patching and repair.

References

1. Wells, Danny, Meade, Bobby W., Hopwood, Theodore II, and Palle, Sudhir, "*A Programmatic Approach to Long-Term Bridge Preventive Maintenance*", Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky, March 2017.
2. "*Section 4: Bridge Deck Repair*", Texas Department of Transportation Online Manuals, Austin, Texas, May 2018.
3. "*PN 512-01/21/11-Item Special-Patching Concrete Bridge Decks*", Ohio Department of Transportation, January 2011. Available at dot.state.oh.us/divisions/construction_mgt.

4. Bowman, Mark D. and Moran, Luis M., “*Bridge Preservation Treatments and Best Practices*”, Joint Transportation Research Program, Report # FHWA/IN/JTRP-2015/22, West Lafayette, Indiana, 2015.
5. “*Deck Stab Repair*”, Illinois Department of Transportation, April 2018. Available at www.idot.illinois.gov/assets/uploads.

Beam and Girder Repair

Both fiber-reinforced polymer (FRP) and fabric-reinforced-cementitious matrix (FRCM) are widely studied for repair and strengthening of damaged girders. As stated by Pino, et al. (1), FRCM is a composite material consisting of a sequence of one or more layers of cement-based matrix reinforced with dry-fiber fabric. FRP consists of a sequence of one or more plies of unidirectional fibers embedded in organic resin. Use of composite materials has gained in popularity due to their excellent material behavior and ease of application (2).

Numerous case studies have been published in the last five years, including one on US-90 in southern Louisiana (3), two bridges in Kentucky that were repaired with steel fiber reinforced polymer sheets (4), and Vermont (5). Work for the Illinois Department of Transportation by Andrawes, et al. (6) evaluated FRP with glass and carbon laminates as well as near surface mounted carbon reinforced bars or plates. Their study included effects of freeze-thaw cycling. They recommended use of FRP laminates for girders with damaged end regions.

The long term performance of external FRP-epoxy-concrete interface bonding is a concern. Pallemati, et al. (7) conducted pull-off testing of FRP interface bonding. While most of the tests failed in the concrete, indicating strong bond, the results had considerable scatter in both bond strength and failure mode.

Jones, et al. (8) compared performance of use of strand splices, FRP, FRCM, and a combination of FRCM and strand splices. They found the FRP repair resulted in the greatest percentage of original strength, followed by the combination of FRCM and strand splices. They recommended fatigue testing of FRCM prior to deployment. Work by Kasan, et al. (9) also tested a combination approach using internal strand splicing and externally bonded carbon FRP. They found that the combined approach maximized the degree of damage that could be repaired.

Zmetra, et al. (10) reported on use of ultra-high performance concrete (UHPC) to encase corrosion in damaged steel girder ends. UHPC panels were attached to the girders with shear studs welded to the web and flange surrounding the corroded area. The UHPC panels provide a new load path, increasing the bearing capacity of the girder.

Beam end protection treatments were the subject of a Synthesis by Radlinska, et al. (11). They reported that many agencies use a wide variety of coating and treatments, which they rate as performing well. However, there was no consensus or willingness to suggest products that are most promising or advanced. The authors suggest that a comprehensive laboratory investigation may be required to allow selection of the most suitable treatments and coatings.

References

1. Pino, Vanessa; and Nanni, Antonio; “*FRCM and FRP Composites for the Repair of Damaged PC Girders*”, University of Miami, Coral Gables, Coral Gables, FL, Report 00042134-04, June 2017.
2. Pino, Vanessa, Nanni, Antonio, Arboleda, Diana, Roberts-Wollmann, Carin, and Cousins, Thomas, “*Repair of Damaged Prestressed Concrete Girders with FRP and FRCM Composites*”, Journal of Composites for Construction, American Society of Civil Engineers, Vol 21, Issue 3, June 2017.
3. Tsai, Ching, Feng, Dana, D’Andrea, Arthur, and Carpenter, Brice, “*A Case Study of Carbon FRP Repair of Precast, Prestressed Girders*”, TRB 93rd Annual Meeting Compendium of Papers, Transportation Research Board, Washington, D.C., Paper 14-2771, Jan. 2014.
4. Choo, Ching Chiaw, Peiris, Abheetha, and Harik, Issam E, “*Repair Using Steel Fiber Reinforced Polymer on US 150 Bridges*”, University of Kentucky, Lexington, KY; Report KTC-13-17, Oct. 2013.
5. Colgrove, George W, III, “*Assessment of Mechanically Fastened Fiber-Reinforced Polymer (MF-FRP) Strips for Extending Bridge Service Life*”, Vermont Agency of Transportation, Montpelier, VT, Report 2015-08, March 2015.
6. Andrawes, Bassem, Shaw, Ian D., and Zhao, Hang, “*Repair & Strengthening of Distressed/Damaged Ends of Prestressed Beams with FRP Composites*”, University of Illinois, Urbana, Urbana, IL, Report FHWA-ICT-18-001, Feb. 2018.
7. Pallemapati, Hemachand, Beneberu, Eyosias, and Yazdani, Nur, “*Condition Assessment of Fiber-Reinforced Polymer Strengthening of Concrete Bridge Components*”, Journal of Performance of Constructed Facilities, American Society of Civil Engineers, Volume 30, Issue 6, Dec. 2016.
8. Jones, Mark, Gangi, Michael, Leisen, Justin, Pino, Vanessa, Roberts-Wollmann, Carin L, Cousins, Thomas, Koutromanos, Ioannis, Nanni, Toni, and Zhou, Jiaxing, “*Evaluation of Repair Techniques for Impact Damaged Prestressed Beams*”, Virginia Center for Transportation Innovation and Research, Charlottesville, VA, Report CAIT-UTC-035, April 2017.
9. Kasan, Jarret, Harries, Kent, Miller, Richard, and Brinkman, Ryan, “*Repair of Prestressed-Concrete Girders Combining Internal Strand Splicing and Externally Bonded CFRP Techniques*”, Journal of Bridge Engineering, American Society of Civil Engineers, Volume 19, Issue 2, pp 200-209, Feb. 2014.
10. Zmetra, Kevin M, McMullen, Kevin F, Zaghi, Arash E, and Wille, Kay, “*Experimental Study of UHPC Repair of Corrosion-Damaged Steel Girder Ends*”, Journal of Bridge Engineering, American Society of Civil Engineers, Volume 22, Issue 8, May 2017.
11. Radlinska, Aleksandra, McCarthy, Leslie Myers, Matzke, James, and Nagel, Francis, “*Synthesis of DOT Use of Beam End Protection for Extending the Life of Bridges*”, International Journal of Concrete Structures and Materials, Springer Publishing, Volume 8, Issue 3, pp. 185-199, Sept 2014.

Pin and Hanger Replacement

Linzell, et al. (1) reported on five approaches to replacing pin and hanger assemblies:

1. Replace with bolted splices,
2. Replace with link slab,
3. Install a catcher beam system,

4. Replace with a ship lap joint, or
5. Replace with a new pin and hanger assembly.

In a state survey, most states used catcher beam system, replaced with a new pin and hanger, or replaced with bolted splice. In this survey, Michigan reported having 1,099 pin and hanger assemblies, all girder bridges, and provided a detail they use for this work.

The catcher beam system provides a secondary catcher beam to carry the loads across the expansion joint. This is a temporary system but protects against failure of the pin and hanger system.

Replacement with another pin and hanger assembly was the most common approach, and one that minimizes traffic delays. FHWA recommends use of stainless steel pins and hangers with larger cross sections. This approach still provides a non-redundant system for a fracture critical portion of the bridge.

Notes on Michigan Activities

North region included Pin and Hanger replacement in year 30 of their original bridge activity list. Details of the survey results and region activity lists can be found in Chapter 5.

Reference

1. Linzell, Daniel G, Balakrishna, Chandana C, “*Steel Pin and Hanger Replacement Options*”, Mid-America Transportation Center, University of Nebraska-Lincoln, Lincoln, NE, Report No 26-1121-40310991, Jan 2017.

New Technologies

In the process of conducting this literature review, several new processes or applications were identified. These are not currently ready for application but are worth considering for future development.

Singhal, et al. (1) reported on a LADAR-based collision warning sensor that can be installed on the face of a structure and measure the height of an on-coming vehicle in time that the vehicle could stop before hitting the structure. The technique is patent pending, and the prototype can measure height with an accuracy of plus or minus 0.66 inches.

Two emerging technologies are related to polymer or epoxy concrete. Douba, et al. (2) reported on use of carbon nanotubes to improve the fracture toughness of polymer concrete. Ai, et al. (3) reported on effects of microwave curing on the chemical and physical properties of epoxy asphalt. The intent is to reduce the curing time, and the study showed better ductility compared with curing by conventional heating.

A project is underway at Purdue University (4) to develop a new class of self-healing cementitious composites with ultra-high ductility and durability that can heal cracks in concrete caused by shrinkage, freeze-thaw damage, and traffic loading.

Guo, et al. (5) reported on development of a new concrete with internal curing. This process uses prewetted lightweight aggregate with a low water to cement ratio. The high performance concrete minimizes shrinkage cracking and increases hydration to reduce chloride ingress.

Two technologies were directed at developing systems that allowed easier and more rapid removal of either the bridge deck or other bridge elements. Work by Li, et al. (6) reported on large-scale composite NU I-girders with a connection that allows removal of the bridge deck with a 2/3 reduction in effort. Suwaed and Karavasilis (7) reported on development of a demountable shear connector for precast steel-concrete composite structures. They report that use of the connectors can allow precast deck panels to be raised and replaced, connectors can be rapidly removed and replaced, and steel beams can be replaced, and precast decks and shear connectors can be reused.

References

1. Singhal, Abhishek, Kamga, Camille, and Agrawal, Anil Kumar, “*LADAR-based Collision Warning Sensor to Prevent Over-Height Vehicle Bridge Hits*”, IET Intelligent Transport Systems, Institution of Engineering and Technology, Volume 12, Issue 7, pp 689-695, Sept. 2018.
2. Douba, Ala Eddin, Emiroglu, Mehmet, Tarefder, Rafiqul A, Kandil, Usama F, Reda Taha, Mahmoud, “*Use of Carbon Nanotubes to Improve Fracture Toughness of Polymer Concrete*”, Transportation Research Record, Transportation Research Board, Washington, D.C., Issue 2612, pp. 96-103, 2017.
3. Ai, Tao, Xiang, Shu, and Wang, Zhenjun, “*Effects of Microwave Curing on the Chemical and Physical Properties of Epoxy Asphalt*”, Journal of Materials in Civil Engineering, American Society of Civil Engineers, Volume 28, Issue 11, Nov. 2016.
4. Lu, Na (PI), “*Self-Healing Cementitious Composites (SHCC) with Ultrahigh Ductility for Pavement and Bridge Construction*”, Purdue University, West Lafayette, IN, Contract SPR-4326, ongoing.
5. Guo, Yuntao, He, Xiaozheng, Peeta, Srinivas, Zheng, Hong, Barrett, Tim, Miller, Albert, and Weiss, W. Jason, “*Internal Curing as a New Tool for Infrastructural Renewal: Reducing Repair Congestion, Increasing Service Life and Improving Sustainability*”, NEXTRANS, Purdue University, West Lafayette, IN, Report NEXTRANS 082py04, April 2014.
6. Li, Chaohui, Lequesne, Remy D, and Matamoros, Adolfo, “*Composite Action in Prestressed NU I-Girder Bridge Deck Systems Constructed with Bond Breakers to Facilitate Deck Removal*”, University of Kansas, Lawrence; Lawrence, KS, Report K-TRAN: KU-15-1, Nov. 2017.
7. Suwaed, Ahmed S H, and Karavasilis, Theodore L, “*Novel Demountable Shear Connector for Accelerated Disassembly, Repair or Replacement of Precast Steel-Concrete Composite Bridges*”, Journal of Bridge Engineering, American Society of Civil Engineers, Volume 22, Issue 9, June 2017.

Life Cycle Analysis, Whole Life Costing, and Life Cycle Planning

Life-cycle cost analysis (LCCA) is an economic tool to determine the most cost-effective option among various alternatives to purchase, own, operate, maintain and, finally, dispose of an asset, when each option could be selected based on technical grounds. For example, for a highway pavement, in addition to the initial construction cost, LCCA will consider agency costs related to future activities, including future periodic maintenance and rehabilitation, and may take into account all the user costs (e.g., reduced capacity at work zones). LCAA is an economic analysis that may be performed for a project or corridor and frequently, is used by agencies to make pavement type decisions. It requires detailed

information about different designs, treatment costs, expected treatment lives, traffic counts and hourly distributions, construction periods, and methods of traffic control.

For network level analysis or planning, whole life costing or life cycle planning (LCP) is used. LCP is defined in the FHWA's published rule of October 26, 2016 as *"a process to estimate the cost of managing an asset class or asset sub-group, over its whole life with consideration for minimizing cost while preserving or improving the condition."* (1). LCP should contain a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement to achieve the desired condition and performance over the period of the analysis.

The purpose of LCP is to compare the resulting asset condition for various alternatives for an equal level of funding. According to the FHWA, *"agencies have found that asset strategies employing low-cost treatments that extend service life, preserve desired asset conditions longer, and postpone the need for rehabilitation can be effective"* in reaching performance targets (1).

An agency must define its asset classes or sub-groups and consider a list of potential work activities along with their unit costs and their expected service lives. Minnesota has published deterioration rates for concrete bridge decks. They found that type of deck reinforcement (epoxy coated versus uncoated) and location within the state were the most influential factors. The Minnesota Metro District showed the most rapid rate of deterioration, and all other districts showed lower and similar rates. They attribute this higher rate of deterioration for the Metro District to higher Average Daily Traffic, more frequent application of de-icing chemicals, and to delayed implementation of deck crack sealing. The results of this study led to the creation of 6 classes for concrete bridge decks in Minnesota. (2). The Michigan Department of Transportation has a list of potential work activities as well as guidelines for when each should be used based on bridge deck condition. Table 2.5 shows the treatment repair options and anticipated service lives for decks with uncoated rebar (3). The previously mentioned work to develop an AASHTO guide for bridge preservation by Hearn at the University of Colorado at Boulder will provide some life cycle cost comparisons between scenarios where preservation treatments are and are not part of the life of the bridge.

In cases where funding is constrained, an agency may elect to use its resources on high-volume and high-priority facilities, such as Interstates. Severe funding constraints may require that other portions of the network receive only minimal maintenance. In general, LCP is conducted for the following scenarios:

1. Minimum maintenance only,
2. Meeting minimum performance,
3. Continuation of current funding levels,
4. Funding to maintain current conditions,
5. Target state of good repair, or
6. Reduced funding level.

References:

1. *"Using a Life Cycle Planning Process to Support Asset Management"*, Federal Highway Administration, Office of Asset Management, Washington, D.C., November 2017.

2. Nelson, Sara L., “*Deterioration Rates of Minnesota Concrete Bridge Decks*”, Minnesota Department of Transportation, Office of Transportation System Management, Research Project 2014-40, St. Paul, Minnesota, October 2014.
3. “*Bridge Deck Preservation Matrix- Decks with Uncoated “Black” Rebar*”, Michigan Department of Transportation, Lansing, Michigan, July 2017.

| Deck Condition State | | | | | Potential Result | Potential Result | |
|----------------------|----------------|----------------|----------------|---|-----------------------|--------------------------|------------------------------|
| Top Surface | Top Surface | Bottom Surface | Bottom Surface | | | | |
| BSIR #58a | % Deficiencies | BSIR #58b | % Deficiencies | Repair Options | Top Surface BSIR #58a | Bottom Surface BSIR #58b | Anticipated Fix Life (years) |
| >=5 | NA | NA | NA | Hold with maintenance | No change | | NA |
| >=5 | | | | Silane | | | 5 |
| >=5 | | | | Healer Sealer | | | 8-10 |
| >=5 | <=10 | >=6 | <=2 | Epoxy Overlay | 8,9 | No change | 15-20 |
| >=5 | <=10 | >=4 | <=25 | Deck Patch | 6,7,8 | No change | 5-10 |
| 4 or 5 | 10-25 | >=5 | <=10 | Deep Concrete Overlay | 8,9 | No change | 25-30 |
| 4 or 5 | 10-25 | 4 | 10-25 | Shallow Concrete Overlay | 8,9 | No change | 20-25 |
| 4 or 5 | 10-25 | 4 | 10-25 | HMA overlay with waterproofing membrane | 8,9 | No change | 8-10 |
| 4 or 5 | 10-25 | 2 or 3 | >25 | HMA cap | 8,9 | No change | 2-4 |
| <=3 | >25 | >=6 | <2 | Deep Concrete Overlay | 8,9 | No change | 20-25 |
| <=3 | >25 | 4 or 5 | 2-25 | Shallow Concrete Overlay | 8,9 | No change | 10 |
| <=3 | >25 | 4 or 5 | 2-25 | HMA overlay with waterproofing membrane | 8,9 | No change | 5-7 |
| <=3 | >25 | 2 or 3 | >25 | HMA cap | 8,9 | No change | 1-3 |

| Deck Condition State | | | | | Potential Result | Potential Result | |
|----------------------|----------------|----------------|----------------|---|-----------------------|--------------------------|------------------------------|
| Top Surface | Top Surface | Bottom Surface | Bottom Surface | | | | |
| BSIR #58a | % Deficiencies | BSIR #58b | % Deficiencies | Repair Options | Top Surface BSIR #58a | Bottom Surface BSIR #58b | Anticipated Fix Life (years) |
| <=3 | >25 | 2 or 3 | >25 | Replacement with epoxy coated or stainless rebar deck | 9 | 9 | 60+ |

Table 2:5 Bridge Deck Preservation Matrix for Decks with Uncoated "black" Rebar (Michigan DOT 2017)

Road User Costs

Road user costs are costs to drivers, both commercial trucks and passenger vehicles, due to changes in traffic patterns. They can be used to demonstrate the benefits of added capacity. They can also be used to show the impact to the travelling public of work zones and detours. For pavement rehabilitation projects, including capital preventive maintenance and rehabilitation, the approach to user costs compares “during construction” with “after construction” to find the change from lane restrictions during construction to average speeds situation after construction is completed.

Road User cost has several components:

$$RUC = VOC + AC + VOT$$

Equation 2.1

where RUC = road user cost,
VOC = vehicle operating cost,
AC = accident cost, and
VOT = value of time.

Daniels, Ellis and Stockton (1) make the case for Texas Department of Transportation to use a simplified RUC based on value of time alone. They make the argument that for rehabilitation or construction that does not increase capacity, the vehicle operating costs and accident costs are only negligibly impacted by the project. The major component of RUC for the case with no capacity increase is the VOT (Daniels, et al., 1999). Specifically, for rehabilitation projects that do not increase capacity, the RUC during construction is compared with the RUC under normal traffic flow, i.e., the RUC is estimated by multiplying the delay time caused by the construction by the VOT and by the typical vehicle occupancy.

The VOT rates per hour refer to the hourly value per person. Typical automobile occupancy is 1.3 persons per vehicle. Most states use separate values of time for autos and for trucks and the value of time would be adjusted based on the Consumer Price Index (CPI) (2). The range of values in the 1998 report was between \$8.70 and \$12.60 for automobiles and between \$21.14 and \$50.00 for trucks

(Daniels, et al., 1998). All the lowest VOTs were in southern states. Only Ohio was included in the Texas report, and its values were \$12.60 for automobiles and \$26.40 for trucks.

Reference:

1. Daniels, Ginger, Ellis, David, and Stockton, Wm. R, “*Techniques for Manually Estimating Road User Costs Associated with Construction Projects*”, Texas Transportation Institute, Texas A&M University, College Station, TX, December 1999.
2. Consumer Price Index Tables, Table 24, U.S. Bureau of Labor Statistics, Washington, D.C., 2018.

Approach for User Delay Costs

Calculation of user delays, and the cost (value) of those delays is complex (1,2). The daily traffic on a bridge is not uniform during the day. Using the vehicle distribution, statewide average, for the road segment on which the bridge is located will give the number of vehicles in each hour of the day and night on the bridge. That traffic stream consists of automobiles and a variety of heavier vehicles. To make the data requirements manageable, we will consider automobiles, and total trucks (a combination of single unit and tractor trailer vehicles), with each making up a percentage of the average annual daily traffic for the year in which the activity takes place.

Automobile traffic consists of both vehicles on business travel as well as those on personal trips. The 2017 National Household Travel Survey (3) provides the estimate of the percentage of trips in each category. The document also provides the average vehicle occupancy rates for business and for overall personal automobile trips (1.24 and 1.67 respectively). Time for personal travel was valued at 50% of the median annual income for Michigan, using the Michigan Household Income from the Department of Numbers (4) and 2080 hours per work-year. Time for business travel was valued at 100% of the median annual income, consistent with FHWA Office of Operations methodology. A weighted average of business and personal automobile values is used to calculate an hourly time value of passenger cars.

Similarly, single unit trucks and tractor trailers have different average vehicle occupancy rates, percentages of the traffic stream and annual mean wages. Wages were obtained from the May 2018 State Occupational Employment and Wage Estimates for Michigan for Transportation and Material Moving Occupations (5,6). Average vehicle occupancy rates of 1.025 for single unit trucks and 1.12 for tractor trailer trucks were used. The weighted hourly value of delays for all trucks was calculated using the percentage of single unit and tractor trailer trucks using the combined truck percentage from the traffic database compiled for this project.

Estimating the user cost due to a work zone can include many components. The cost of user delay due to reduced speed in the work zone and the cost of reduced speed in a queue, if one exists, are the largest components. There are other components: cost of fuel for the additional operating time in the work zone, vehicle depreciation, cost of delayed freight deliveries, environmental costs associated with queues, and others. For purposes of this project, only the costs due to reduced speed and queuing are included. (7, 8,9)

Inputs: AADT, ADTT

% light vehicles

% commercial vehicles (total of all trucks)

Posted speed without work zone, posted speed for trucks, posted speed in work zone.

Use statewide average hourly adjustment factors from Michigan DOT User Guide for Mechanistic Empirical Pavement Design, November 2017 (10) to calculate number of vehicles per hour. See Table 2.6.

| Hour | Statewide avg % | Vehicles during hour (AADT*.01*statewide avg for hr) |
|-------|-----------------|--|
| 12 am | 1.62 | |
| 1 | 1.45 | |
| 2 | 1.46 | |
| 3 | 1.75 | |
| 4 | 2.27 | |
| 5 | 3.16 | |
| 6 | 4.29 | |
| 7 | 5.38 | |
| 8 | 6.39 | |
| 9 | 6.67 | |
| 10 | 6.71 | |
| 11 | 6.71 | |
| 12 | 6.55 | |
| 1 pm | 6.44 | |
| 2 | 6.24 | |
| 3 | 5.93 | |
| 4 | 5.25 | |
| 5 | 4.57 | |
| 6 | 3.88 | |
| 7 | 3.35 | |
| 8 | 2.90 | |
| 9 | 2.58 | |
| 10 | 2.27 | |
| 11 | 2.18 | |

Table 2:6 Hourly traffic distribution factors for Michigan

For daytime work, assume work zone set up begins at 9 am and work zone must be removed by 4 pm. Activities with a duration of 5 hours or less can occur in a single day of work. For nighttime work, will use 8 pm to 6 am. Activities with a duration of 8 hours or less can occur. These durations allow 1 hour to set up and 1 hour to end traffic control.

When there is no queue, the delay per vehicle can be calculated as:

$$\text{Delay per vehicle} = Lwz * \left(\frac{1}{\frac{uf}{2}} - \frac{1}{uwzsl} \right) \quad \text{Equation 2.1}$$

For example: Delay/vehicle=1mile (1/25mph -1/45mph) =.018 hr.

When there is a queue, the delay per vehicle increases by:

$$\text{Queue Delay} = Lq \left(\frac{1}{uq} - \frac{1}{uwzsl} \right) \quad \text{Equation 2.2}$$

And the speed in queue is calculated:

$$Uq = \left(\frac{uf}{2} \right) \left(1 - \left(1 - wz \frac{\text{capacity}}{\text{normal}} \right)^{0.5} \right) \quad \text{Equation 2.3}$$

Where Lwz is the length of the work zone in miles,

uf is the speed limit without the work zone

uwzsl is the speed limit in the work zone

Uq is the speed in the queue

Wz capacity is the number of vehicles per hour passing through the work zone

Normal capacity is the number of vehicles per hour without a work zone.

Value of Delay time:

Use average vehicle occupancy rates: work related: 1.24

Personal travel: 1.67

Intercity travel: 2.30

The value of time for local personal travel is determined using 50% of the median annual income divided by 2080 work hours per year. This is multiplied by the respective average vehicle occupancy rate to obtain the hourly value of time per vehicle hour. When traveling by automobile on business, the value of time is based on 100% of the median annual income per hour and is calculated using the average occupancy for business travel. A weighted average of value of time for automobiles is calculated based on the percentage of automobiles travelling on business.

A similar calculation is made to determine the weighted value of delay for both single unit and tractor trailer trucks using their respective mean wages and average vehicle occupancy.

References for User Delay Costs

1. "Estimating performance Measures-A Primer on Work Zone Safety and Mobility Performance Measurement", Federal Highway Administration, Work Zone Mobility and Safety Program, Washington, DC, download May 9, 2019.
2. "Work Zone Road User Costs-Concepts and Applications," Chapter 2, Federal Highway Administration, Office of Operations, p. 1-33. Download May 9, 2019.
3. McGuckin, N. and Fucci, A., "Summary of Travel Trends: 2017 National Household Travel Survey," Table 5a, U.S. Department of Transportation, Federal Highway Administration, FHWA-PL-18-019, July 2018.

4. "Michigan Household Income- 2017", Department of Numbers, Michigan, Lansing, Michigan , download of May 24, 2019.
5. "Occupational Employment Statistics: May 2018 State Occupational Employment and Wage Estimates- Michigan," Office of Employment Statistics, Washington, DC.
6. "Employer Costs for Employee Compensation- December 2018", Bureau of Labor Statistics, U.S. Department of Labor, Document USDL-19-0449, March 19, 2019.
7. Edara, Praveen, and Cottrell, Benjamin, Jr., "Estimation of Traffic Mobility Impacts at Work Zones: State of the Practice," Compendium of papers, Transportation Research Board 2007, Washington, DC., pp 1-14.
8. Weng, Jinxian, and Meng, Qiang, "Estimating Capacity and Traffic Delay in Work Zones: An Overview," Transportation Research Part C: Emerging Technologies, Science Direct, Volume 35, October 2013, pp. 34-45.
9. "616.13 Work Zone Capacity, Queue and Travel Delay," Engineering Policy Guide, Missouri Department of Transportation, Jefferson City, Missouri, June 29, 2017, pp 1-6.
10. "Michigan DOT User Guide for Mechanistic-Empirical Pavement Design," Interim Edition, Michigan Department of Transportation, Construction Field Services Division, Lansing, Michigan, November 2017, Appendix B.4- Hourly adjustments.

Chapter 3 National Survey

Two surveys were completed for this project and will be described, along with their results in Chapters 3 and 5. The first survey was distributed nationally and produced fourteen responses. This survey asked respondents which treatments they use, how long those treatments last, and how long it took to construct each treatment. Respondents were also asked for products or processes they use to speed bridge preservation activities. This component of the national survey is included in Chapter 4.

The second survey was directed at bridge management engineers in the Michigan's seven regions. They were asked to react to the results of the national survey. For example, did they agree with the survey's stated durations required to conduct specific bridge activities? In addition, they were asked to show on a timeline specific activities they would do over the 75-year bridge life span. This survey and its' results is presented in Chapter 5.

National Survey

A list of bridge treatment activities was compiled using a list of Michigan activities combined with a list of activities from a survey conducted by the Midwest Bridge Preservation Partnership (MWBPP). The MWBPP survey was limited to the member states of the regional partnership and focused on which treatments were used and how long they were expected to be effective. The list of treatments included in the national survey is shown in Table 3.1.

For each activity, the respondents were asked to provide a range of treatment service life in years and construction duration for Moderate traffic and for High traffic levels. Treatment life in years was provided for low and high service lives for each activity. Drop down lists in the duration fields were used to reduce the effort in completing the survey. Example durations are 2 to 3 hours, 3 hours to one work day or work night, and 3 to 7 days. In addition, agencies were asked whether each activity would be performed with agency forces or by contract, or a mixture of both agency and contractor efforts.

Respondents were asked about the traffic control used for various durations of activities ranging from 2 to 3 hours to more than 12 months. They were asked about the impact of staging, or maintenance of traffic flow during construction. Specifically, they were asked the impact of staging on the duration of work and about additional work activities associated with staging.

Finally, they were asked about specific activities that would be combined into a single bundle (for example, Indiana DOT indicated that they would combine bridge deck crack sealing with bridge deck broadcast sealing, with a combined duration of 4 to 7 hours). Bundling identifies activities that can be done concurrently or immediately following each other to reduce traffic impacts. Bundling has the potential to reduce total activity times and thus reduce user delay costs.

| Bridge Activities List | Bridge Activities List |
|------------------------------------|-------------------------------|
| Approach pavement relief joints | Patch superstructure spalling |
| Joint sealing/repair | Minor substructure patching |
| Deck crack sealing | Joint replacement |
| Epoxy inject superstructure cracks | Epoxy overlay |

| Bridge Activities List | Bridge Activities List |
|-----------------------------------|--|
| Healer sealer | HMA overlay with waterproofing membrane |
| Coat concrete barrier/deck fascia | HMA overlay with no waterproofing membrane |
| Coat concrete substructure | Paint-complete |
| Coat concrete beams | Paint-zone |
| Seal abutments and caps | Pin and hanger replacement |
| Metal mesh panels | Bridge barrier railing replacement |
| Spot painting | Bearing replacement |
| Superstructure wash | Drain system replacement |
| Deck cleaning/washing | Approach slab replacement |
| Drain system clean/repair | Deep concrete overlay |
| Clean and reset bearings | Major substructure repair |
| Lubricate bearing and seat | Superstructure repairs |
| Level bridge approach | Substructure replacement |
| Bridge barrier railing repair | Deck replacement |
| Thrie beam retrofit | Superstructure replacement |
| Deck patching- partial-depth | Bridge Replacement |
| Deck patching- full-depth | |

Table 3:1 Bridge Activities List

National Survey Results

The locations of the survey respondents are shown on the map in Figure 3.1. Getting sufficient responses required multiple rounds of survey distribution and personal requests. After consultation with the research project panel, we focused our efforts on the northern tier states which have climates similar to Michigan's. Seven Midwest states participated, along with two agencies from the Northeast and five from the Southeast.

Treatment Life Expectations

Four common treatments used by many of the responding agencies are shown in Table 3.2 and demonstrate the results of the national survey regarding treatment life expectancy. Joint sealing repair is a preservation treatment that prevents degradation of members below the bridge joint by blocking water and incompressible debris and deleterious materials from passing from the deck to the beams, bearings and substructure elements. Healer sealers are used to reduce infiltration of salts into concrete bridge elements. In considering Table 3.2, note that one state reported a high life expectancy of 30 years, significantly higher than other agencies. If the one reported high life expectancy of 30 is removed, the average high drops to 11 years. Epoxy overlays also reduce infiltration of salts into the deck, but also provide a wearing course.

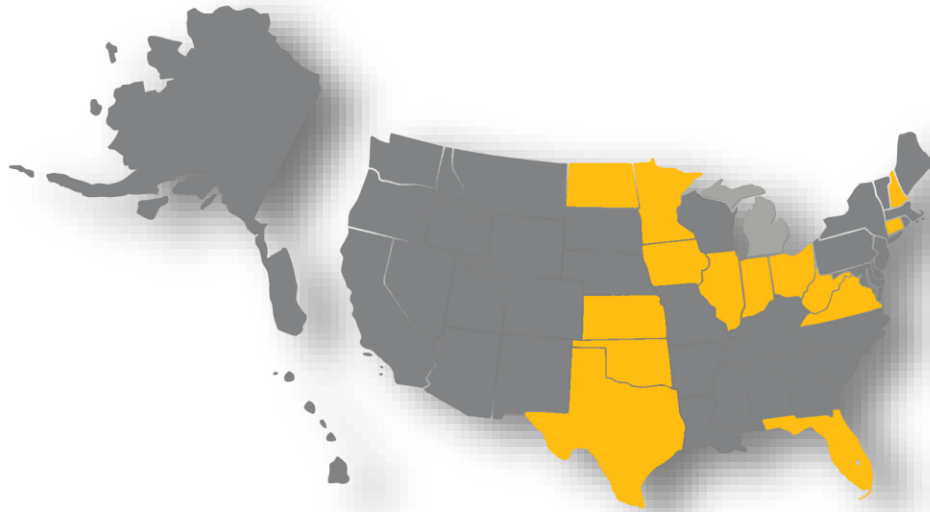


Figure 3-1 Agencies Responding to the National Survey

| Treatment | # of states | Treatment Life (years) | | | |
|----------------------|-------------|------------------------|-----------|--------------|------------|
| | | Average Low | Low Range | Average High | High Range |
| Joint sealing repair | 7 | 3.75 | 2-5 | 12.44 | 10-15 |
| Healer sealer | 6 | 9.17 | 3-15 | 14.29 | 5-30 |
| Epoxy overlays | 9 | 8.56 | 5-15 | 15.22 | 10-25 |
| Joint replacement | 12 | 9.91 | 3-20 | 17.58 | 5-30 |

Table 3:2 Treatment Life Expectations

The results for joint replacements showed even more variability between agencies. The paired lows and highs for joint replacement are shown graphically in Figure 3.2. The difference between the high life expectation and the low life expectation ranged from zero to 25, with two-thirds of the differences being 8 years or less.

Deck replacement is a common, if infrequent, bridge rehabilitation activity. The low range of bridge deck replacement life expectancy was between 15 and 50 years, with half of the reporting agencies estimating 30 years as a low life expectancy. The high life expectancy range for a bridge deck replacement was between 30 and 75 years, with half of the agencies estimating 40 years as the high estimate.

The average life expectancy for a bridge replacement was 68.6 years. The low range was 40 to 75 years, and the high range was 50 to 100 years.

A comparison was made between no-freeze agencies and the upper tier of wet-freeze agencies. Four bridge activities were selected: partial-depth concrete repair, full-depth concrete repair, epoxy overlay and deck replacement. The average life expectancy for a partial-depth repair was 8 years for the no-freeze agencies and 10.6 years for the wet-freeze agencies. Full-depth patches were expected to last

12.5 years for the no-freeze agencies and 13.6 years for the wet-freeze agencies. The regional relationship shifted for the epoxy overlays, with the no-freeze agencies expecting 16.25 years of life, while the wet-freeze agencies reported an average of only 10.3 years. Similarly, deck replacement life in the no-freeze environment was estimated at 62.5 years, while it averaged only 33.12 years in the wet-freeze region.

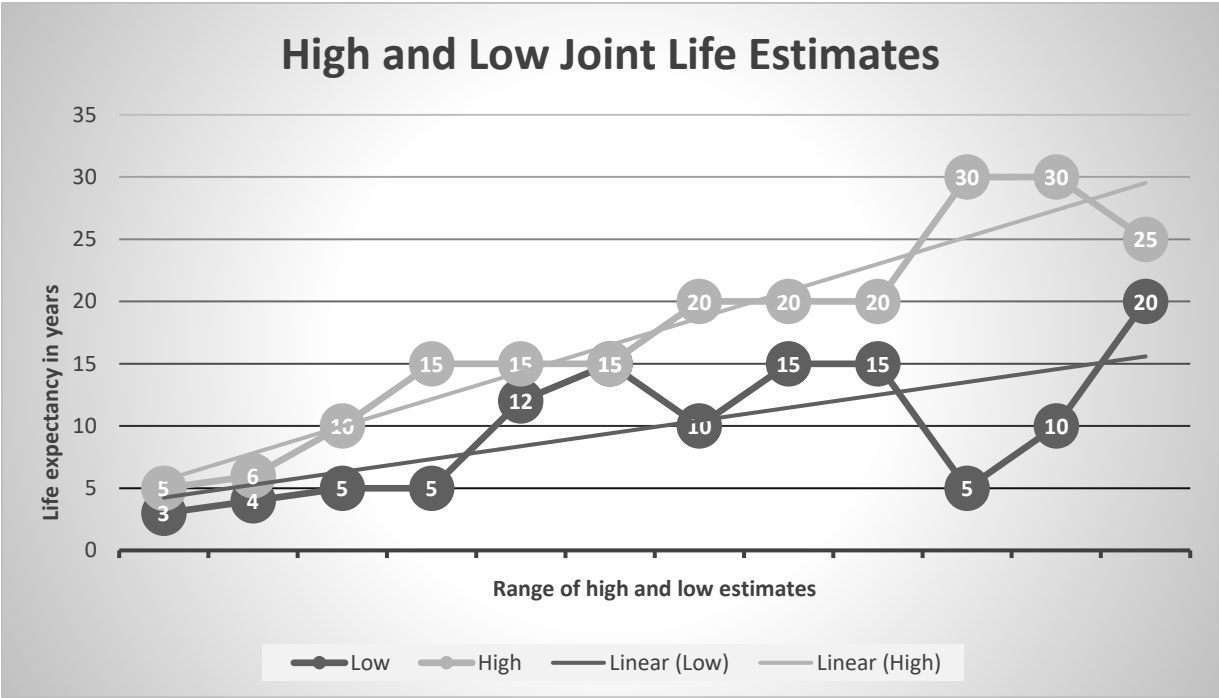


Figure 3-2 Life Expectancy for Joint Replacements

Self-Performed Versus Contracted Work Activities

There was a wide range of reported work activities that are self-performed by agencies or contracted out. Texas reported using state forces only for patching superstructure spalling and application of a hot-mixed asphalt overlay with waterproofing membrane. All other activities were done using contractors. Indiana, on the other hand, used state forces to perform activities including approach pavement relief joints, joint sealing and repair, deck crack sealing, deck cleaning and washing, drain system cleaning and repair, full and partial-depth patching and joint replacement, among others. New Hampshire reported using state forces, as well as contractors, to do bridge replacements. Most agencies that used agency workers for some activities, used contractors for work that would generally be classified as bridge rehabilitation or reconstruction. These heavier activities included deck replacement, substructure replacement, superstructure replacement, and bridge reconstruction. Some “lighter” activities are also now done predominantly by contract. These include leveling bridge approaches, joint replacement, epoxy overlay, HMA overlays with and without waterproofing membrane, and zone and complete painting.

Other bridge activities that historically were done using state forces are now done with a mix of contracted work and self-performed work. Full and partial-depth deck repairs, joint sealing and repair,

as well as spot and zone painting fall in this category. Even deck washing and deck crack sealing is now done with a mixture of contracts and self-performed work.

Table 3.3 shows the number of agencies using contractors, a mix of contracting and state forces, and self-performing for each of the bridge activities. Note that not every agency performs a particular activity. The trend toward more use of contractors for capital maintenance, preservation and light rehabilitation work has been going on for more than a decade. State agencies have generally reduced their personnel complements, by both attrition and reductions in force. The shift has potential impacts on the time to complete bridge activities, as contracts typically allow a wider time period for performance.

| Activity | Contracted | Mix of Contract/State | Agency Performed |
|------------------------------------|-------------------|------------------------------|-------------------------|
| Approach pavement relief joints | 2 | 2 | 2 |
| Joint sealing/repair | 3 | 5 | 2 |
| Deck crack sealing | 3 | 3 | 3 |
| Epoxy inject superstructure cracks | 4 | 2 | 1 |
| Healer sealer | 2 | 3 | 1 |
| Coat concrete barrier/deck fascia | 3 | 2 | 0 |
| Coat concrete substructure | 3 | 2 | 0 |
| Coat concrete beams | 3 | 2 | 0 |
| Seal abutments and caps | 0 | 3 | 1 |
| Metal mesh panels | No responses | No responses | No responses |
| Spot painting | 2 | 4 | 1 |
| Superstructure wash | 2 | 0 | 4 |
| Deck cleaning/washing | 3 | 1 | 3 |
| Drain system clean/repair | 2 | 2 | 3 |
| Clean and reset bearings | 2 | 4 | 2 |
| Lubricate bearing and seat | 2 | 1 | 2 |
| Level bridge approach | 5 | 1 | 1 |
| Bridge barrier railing repair | 4 | 2 | 1 |
| Thrie beam retrofit | 5 | 1 | 0 |
| Deck patching- partial depth | 4 | 4 | 1 |
| Deck patching- full depth | 5 | 2 | 1 |
| Patch superstructure spalling | 2 | 5 | 1 |
| Minor substructure patching | 3 | 4 | 2 |
| Joint replacement | 5 | 4 | 1 |
| Epoxy overlay | 7 | 2 | 0 |
| HMA overlay with WPM | 3 | 2 | 0 |
| HMA overlay w/o WPM | 4 | 0 | 0 |
| Paint-complete | 10 | 0 | 0 |
| Paint-zone | 6 | 4 | 0 |
| Pin and hanger replacement | 7 | 0 | 0 |

| Activity | Contracted | Mix of Contract/State | Agency Performed |
|------------------------------------|------------|-----------------------|------------------|
| Bridge barrier railing replacement | 8 | 1 | 0 |
| Bearing replacement | 6 | 2 | 0 |
| Drain system replacement | 4 | 1 | 0 |
| Approach slab replacement | 8 | 0 | 0 |
| Deep concrete overlay | 7 | 1 | 0 |
| Major substructure repair | 7 | 1 | 0 |
| Superstructure repairs | 6 | 3 | 0 |
| Substructure replacement | 4 | 1 | 0 |
| Deck replacement | 8 | 2 | 0 |
| Superstructure replacement | 6 | 2 | 0 |
| Bridge Replacement | 7 | 2 | 0 |

Table 3:3 Number of Agencies for Activities done by Contractor, Agency Forces or a Combination. Note that WPM is waterproofing membrane.

Activity Construction Durations

The duration of bridge treatment activities is needed in order to calculate the user delay and user delay costs caused by the construction activities. The national survey asked each respondent to provide a range of durations for each activity for both moderate average daily traffic and high average daily traffic.

A list of duration ranges was provided as a drop-down to facilitate data entry by the respondents. The overall time range is very broad because the activities range from deck washing to bridge reconstruction. The duration choices included the following:

- 2 to 3 hours
- 3 hours to one work day or one work night
- 1 to 3 days
- 3 to 7 days
- 7 days to 1 month
- 1 to 3 months
- 3 to 6 months
- 6 to 12 months
- More than 12 months.

Table 3.4 shows the resultant construction durations for each of the bridge activities for both moderate traffic and high traffic situations. Some bridge activities showed almost no change in duration between the two traffic levels. These included joint sealing/repair, healer sealer, drain system cleaning and repair, minor substructure repair and major substructure repair, among others.

Other bridge activities showed a modest impact of traffic level, with high traffic locations having a higher activity duration. For example, bearing replacement had a moderate traffic duration range of 20.56 to 47.44, but a high traffic duration of 24.20 to 60.3. Other activities with moderate traffic

impacts included epoxy inject superstructure cracks, clean and reset bearings, level bridge approach, bridge barrier railing repair, Thrie beam retrofit, bridge barrier railing replacement and deck replacement.

Finally, there were bridge activities that showed a significant increase in activity duration due to traffic level. An example is coating concrete beams, where the moderate traffic range was 3.5 to 9.25 days, but the high traffic duration range was 8.28 to 24.2 days. Other activities with significant traffic level impacts on the estimated activity durations were coat concrete barrier/deck fascia, coat concrete substructure, spot and full painting, full-depth deck patching, joint replacement, drain system replacement, deep concrete overlay, superstructure replacement, and bridge replacement.

The duration of bridge activities is critical to calculation of user delays and user delay costs. Having ranges of construction durations also allows an agency to compare its' expected durations against other agencies and identify activities that it is constructing slower than peer agencies. By identifying these, an agency can identify practices that could be used to accelerate completion of specific activities.

To the best of our knowledge, the national survey reported here is the first to collect information regarding activity construction durations and this information is a valuable product of this project.

| Activity | Moderate Traffic (days) | High Traffic (days) |
|------------------------------------|--------------------------------|----------------------------|
| Approach pavement relief joints | 0.78 to 1.97 | 0.86 to 2.26 |
| Joint sealing/repair | 1.0 to 3.59 | 1.13 to 4.08 |
| Deck crack sealing | 0.54 to 1.94 | 0.97 to 2.33 |
| Epoxy inject superstructure cracks | 1.44 to 5.38 | 2.21 to 8.33 |
| Healer sealer | 1.79 to 5.17 | 1.13 to 3 |
| Coat concrete barrier/deck fascia | 2.75 to 7.20 | 5.35 to 15.2 |
| Coat concrete substructure | 1.0 to 3.0 | 2.5 to 9.8 |
| Coat concrete beams | 3.5 to 9.25 | 8.28 to 24.2 |
| Seal abutments and caps | 2.20 to 5.88 | 2.48 to 6.8 |
| Metal mesh panels | No response | No response |
| Spot painting | 5.71 to 16.23 | 7.20 to 21.43 |
| Superstructure wash | 0.45 to 1.15 | 0.46 to 1.20 |
| Deck cleaning/washing | 0.43 to 1.11 | 0.59 to 1.67 |
| Drain system clean/repair | 0.29 to 1.02 | 0.45 to 1.20 |
| Clean and reset bearings | 2.09 to 6.63 | 3.00 to 8.11 |
| Lubricate bearing and seat | 0.47 to 1.19 | 0.60 to 1.84 |
| Level bridge approach | 0.80 to 2.34 | 1.52 to 7.75 |
| Bridge barrier railing repair | 0.90 to 2.23 | 1.59 to 4.57 |
| Thrie beam retrofit | 2.67 to 7.17 | 3.86 to 10.85 |
| Deck patching- partial depth | 2.11 to 7.17 | 3.86 to 5.40 |
| Deck patching- full depth | 3.52 to 8.89 | 6.08 to 17.8 |
| Patch superstructure spalling | 0.91 to 2.34 | 0.94 to 2.56 |
| Minor substructure patching | 1.59 to 4.30 | 1.54 to 4.22 |
| Joint replacement | 4.46 to 12.89 | 6.21 to 18.0 |
| Epoxy overlay | 5.63 to 27.14 | 7.13 to 20.12 |
| HMA overlay w/ WPM | 9.80 to 29.20 | 10.20 to 30.0 |
| HMA overlay w/o WPM | 10.19 to 30.50 | 10.34 to 31.0 |
| Paint-complete | 24.56 to 53.33 | 40.78 to 104.0 |
| Paint-zone | 5.42 to 39.88 | 13.00 to 31.22 |
| Pin and hanger replacement | 33.43 to 74.29 | 31.75 to 72.5 |
| Bridge barrier railing replacement | 25.25 to 60.38 | 27.78 to 80.0 |
| Bearing replacement | 20.56 to 47.44 | 24.20 to 60.3 |
| Drain system replacement | 32.20 to 72.0 | 50.8 to 104.0 |
| Approach slab replacement | 25.00 to 57.14 | 24.38 to 57.5 |
| Deep concrete overlay | 12.00 to 35.29 | 15.71 to 46.71 |
| Major substructure repair | 49.57 to 105.71 | 50.88 to 107.5 |
| Superstructure repairs | 30.50 to 68.38 | 32.63 to 80.0 |
| Substructure replacement | 80.0 to 165.0 | 76.0 to 156.0 |
| Deck replacement | 41.89 to 95.56 | 46.0 to 108.0 |
| Superstructure replacement | 90.0 to 188.57 | 120.0 to 210.0 |
| Bridge Replacement | 120.0 to 210.0 | 173.33 to 240.0 |

Table 3:4 Activity Durations for Moderate and High Traffic Levels

Bundling

Bundling is the combining of several activities that will be done concurrently or immediately following each other. Bundling may result in shorter total construction time and therefore reduce user impacts. Bundling may also result in reduced contract costs. If an agency self-performs the work, bundling may allow more efficient use of manpower, with the same crew performing a variety of tasks during the same work period. Agencies were asked to list activities they tend to bundle and include the time required to complete the bundle.

Minnesota bundles crack sealing, joint sealing, rail sealing and minor deck repair together and the work averages one day per bridge for a 10,000 square foot bridge deck. North Dakota bundles minor repairs with bridge inspection with a duration of one to two days.

A frequently used bundle consists of deck repair or deck crack sealing with flood sealing, healer sealer or silane applications. This is used by Texas, Iowa, Indiana and North Dakota. The time to complete the work varies from 4 to 7 hours in Indiana (self-performed) to 1 week in Texas (by contract). Kansas bundles deck patching and a polymer overlay, with a 3 to 6-month time.

Indiana bundles its bridge deck, superstructure and drain cleaning and washing activities into a bundle that typically takes 1 to 2 hours per bridge. North Dakota adds joint and drainage repair to that bundle and estimates the time to complete the bundle at 1 to 2 days per bridge.

Several bundles are used when doing joint replacement. Illinois, Kansas, and New Hampshire combine joint replacement with deck patching. While the work duration depends on deck size, Kansas estimated the combined time at 1 month. Connecticut, Illinois and Iowa bundle joint replacement with a bridge deck overlay, with estimated completion time of 2 to 3 months. Connecticut includes multiple bridges in its bundle. Similarly, Oklahoma issues “joint projects” that consist of joint replacements at multiple bridges over a 3-month period. Oklahoma also issues “paint projects” to handle coatings on multiple bridges over a 3-month period. West Virginia and Virginia combine joint repairs with deck overlays. In the case of Virginia, the work includes hydro-demolition, joint repairs and rigid concrete overlay with very early strength latex modified concrete with rapid set cement. Work is to be completed in four weekends, a total of eight working days.

Texas uses two types of bundles in doing bearing adjustments. In the shorter duration work, full-depth deck repair is bundled with bearing adjustment, with a one-month duration of work. When the bearing adjustment is combined with re-decking, the duration of work increases to six months. Connecticut combines bearing replacements with steel repairs and beam end repairs, with a duration of six to twelve months.

Connecticut also bundles superstructure repair or replacement with substructure repair, with six to twelve months to complete the work.

One additional bundle option was submitted by Illinois. That combined roadway resurfacing with bridge deck sealing and resulted in no additional time.

Staging

Staging is selecting a sequence of construction phases that maintaining traffic flow during construction. It is often associated with higher traffic volumes but may also occur where traffic delays are not tolerated. This may also include situations where preservation work must be done during nighttime hours, or over weekend periods.

Estimates were provided by Indiana, Iowa, Texas, West Virginia, Florida, Minnesota, Kansas and Illinois about the impact on construction duration, which ranged from 10% to 63% increase. The average increase in work duration was 31.3%. New Hampshire reported that night-time work is required when traffic volumes are too high for the number of lanes available. No hard data was available in New Hampshire regarding the percentage increase in time needed.

Florida itemized some of the additional activities that are required for staged work: additional construction joints, additional contractor mobilizations, additional formwork, and traffic maintenance-related items (signs, striping, channelizing devices, traffic control officers, etc.). Other agencies also included additional activities related to traffic control: Indiana uses lane closures, nighttime work, and additional signage; Texas uses lane direction changes, temporary crossovers, and temporary detours; West Virginia uses crossovers and contraflow lanes; and New Hampshire uses variable message boards.

Illinois faces some of the heaviest traffic of any of the responding states. They said, “On roads with extreme congestion we require a smart work zone, which is a series of Changeable Message Signs which are linked with various detectors and give up to date travel times. We also pay the contractor to provide surveillance whenever he isn't working, that there is always someone on or near the job site while the Traffic Control is functional.”

Summary

Chapter 3 has described a national survey of bridge activities, their life expectancies, and their construction durations. The national survey also included information about bundling activities and the impact of bundling on activity duration. Respondents were also asked about the impact of staging, or maintenance of traffic during activity construction, on total project duration. In addition, respondents indicated whether each bridge activity was conducted using in-house forces or contracted out, or a combination of the two.

Chapter 4 includes items identified in the national survey that have been used by other agencies to speed bridge preservation. Michigan region bridge engineers were asked to react to the findings of the national survey in a Michigan-only survey that is described in Chapter 5.

Chapter 4 Speeding Construction of Bridge Preservation

One portion of the national survey asked respondents to identify products or processes they use to speed construction of bridge preservation. Responses were received from 11 agencies. While departments of transportation (DOTs) frequently identify only generic product classes, respondents were asked to provide product specifics if they wished. As a result, specific products and manufacturers are identified in this chapter. The respondents were also asked for the duration of construction of previously used treatments and the construction duration when using the new project or process.

This chapter is divided into bridge activities for which processes or products were identified. Six applications are related to concrete patching. The second section deals with deck overlays, followed by sealants and surface finishes. Joint replacement and resealing are the subject of eight responses. The chapter finishes with a number of products or processes for which a single state provided input.

Concrete Patching

Deck patching is a common bridge preservation activity and a variety of products are available to speed activity completion. Connecticut DOT indicated use of rapid set concrete. Other agencies provided specific product recommendations, which are shown in Table 4.1.

| State Agency | Product | Old Duration | Duration with Product |
|------------------------------------|--|-----------------------------------|-----------------------------------|
| Virginia | RapidSet DOT Concrete Mix (CTS Cement Manufacturing Corp.) | 28 days | 2 hours |
| Minnesota | Elephant Armor (Global Sealer Technologies) with Elephant armor primer and curing compound | 3-5 hrs following patch placement | <1 hour following patch placement |
| Minnesota | Ardex (Construction Materials) | | <1 hour following patch placement |
| Minnesota | Set45 | | <1 hour following patch placement |
| North Dakota | Elephant Armor | 7 days | 2-4 hours |
| North Dakota | Rep Con 928 (Spec Chem LLC) | 7 days | 2-4 hours |
| North Dakota | Pavemend (Aquafin Inc.) | 7 days | 2-4 hours |
| Indiana | Kwik Bond PPC 1121 | 5-7 hours | 3-4 hours |
| Minnesota for overhead or vertical | Elephant Armor | | |
| Minnesota for overhead or vertical | Ardex (Construction Materials) | | |
| Minnesota for overhead or vertical | Emaco GP (BASF) | | |

Table 4:1 Products for Accelerated Deck Patching

Minnesota DOT also uses Phoscrete, which contains magnesium, calcined aluminosilicates, graded aggregates and fibers with a liquid Phosphate Activator. The material attains high early compressive strength, and can be opened to traffic in one hour. It accepts joint sealants and pavement markings after one hour and requires no primer or curing compounds.

Minnesota DOT also provided three product suggestions for overhead or vertical concrete repair. Their older technique used shotcrete, and that is still used for larger areas because it is quicker and less expensive. Shotcrete requires a trained operator for the shotcrete equipment and methods and using it requires equipment mobilization. Minnesota DOT indicated that for smaller repair areas, use of the three products shown in Table 4.1 saves hours in equipment mobilization and set up.

Deck Overlays

Use of Latex Modified Concrete (LMC) for rapid bridge deck overlays was identified by Indiana, Iowa and Virginia. Indiana indicated that they were having a new LMC specification developed for them and that the new process would reduce construction time from 2 to 3 months to 2 weeks. Iowa is using very early strength LMC to reduce construction time from 2-4 weeks to 2 nights or 2 weekends.

Virginia DOT is using very early strength LMC using Rapid Set CTS Cement. The CTS Cement is a high-performance, polymer-modified, fast setting, fiber reinforced concrete repair material that is durable in wet environments. Virginia reports a change in construction duration from 7 days to 3 hours.

Iowa DOT also reported using polyester polymer concrete overlays. They found a reduction in construction time from 2 to 4 weeks down to 2 nights or 2 weekends. One manufacturer of polyester polymer concrete is Kwik Bond Polymers, with product PPC 1121. According to the manufacturer, the material can be placed in a single lift of between 0.75 inches and 12 inches. It can be used for overlays, patching, and for expansion joint headers.

Deck Sealers and Concrete Special Surface Finish

Both Indiana DOT and North Dakota DOT recommend use of Evonik Protectosil for silane sealing of bridge decks. Protectosil BHN is used by Indiana, while Protectosil 300S is used by North Dakota. Protectosil is used for waterproofing of mineral layers, like concrete and the quantity depends of the degree of absorption of the substrate. It is applied by flow-casting to the saturation point by allowing it to flow without pressure against the deck surface. Protectosil should not come in contact with asphalt.

In addition to Protectosil, Indiana DOT listed SIL-ACT ATS-100 as a recommended solvent based silane. This product is produced by Advanced Chemical Technologies, Inc. It is described as a premium grade, clear, penetrating silane-waterproofing treatment. Typical coverage rate is between 200 and 300 square feet per gallon and is considered well suited to high traffic areas. North Dakota also recommended MasterProject H1000. This product is solvent based and excellent for cold weather applications. It is a 100% silane penetrating sealer that penetrates the substrate and protects against chloride ion penetration.

In addition to products recommended above, Minnesota recommended use of an 8-foot spray bar with a wand to accomplish deck flood seal application. This is faster than using a squeegee or Hudson sprayer, reducing the application time from 4 days to ½ day for a typical 200 ft. long bridge.

Minnesota DOT also recommended use of one component materials, like TexCoat, that can be placed on green or uncured concrete to create a special concrete surface finish. This material can be used after forms are stripped and the material has some curing compound benefits as well. The older technique required a 28-day concrete cure with acrylic paint and motor mix.

Joint Repair, Sealing, and Replacement

Joint sealing and repair is a common bridge preservation treatment that prevents chlorides and debris from reaching beams and other substructure elements. Minnesota DOT proposed a modified method to prepare the joint for pourable joint sealing. Their method would partner a saw with a wire wheel to remove material from the joint. This combination would save time in preparation instead of using sand blasting. They propose to tow a rubber melter behind the removal operation, using a small portable melter for smaller projects. They estimated that this approach could cut the activity time in half.

Florida DOT indicated that they have progressed significantly in the use of pourable expansion joint systems that provide superior performance in preventing leakage in comparison to their older expansion joint systems. The ability to spot-repair rather than completely replace is a significant benefit of the new pourable expansion joints. When replacement is needed, Florida DOT provides that in conjunction with highway resurfacing activities, typically on a 12 to 15-year cycle.

Minnesota also has an alternate approach for expansion joint gland or joint replacement. They cut the gland instead of doing a full removal, thus eliminating the cleaning of the extrusion. They leave the extrusion and rubber ears in place to fill void area, or they insert a backer rod which is sealed. Following the gland cutting operation, EMSEAL is inserted to complete the joint repair. The total time for this activity is less than 3 hours. These activities previously took 1 to 2 days for gland replacement and a week or more for joint replacement. Illinois DOT also recommended the EMSEAL product for resealing expansion joints. Specifically, they use BEJS joint system by EMSEAL, and use polymer concrete to repair the joint headers. This work used to take 2 to 3 weeks per stage, and now is handled with multiple overnight temporary closures.

Specific products suggested for use in joint gland repair, resealing expansion joints and joint concrete header repairs are shown in table 4.2.

| Agency(s) | Product |
|-------------------------------|------------|
| Minnesota + Illinois + Kansas | Emseal |
| Minnesota | Belzona |
| Minnesota | Loctite |
| Minnesota | D.S. Brown |
| Kansas | Kwikbond |
| Kansas | Polytite |

Table 4:2 Products for Accelerated Expansion Joint Repair and Replacement

Kansas DOT described their joint replacement process. On the first day of the operation, they remove the old joint header, prepare the area and pour polyester concrete, and let it set up. On the second day, the membrane joint seal is installed to complete the operation. Kansas DOT uses Kwikbond for the polyester concrete headers and either EMSEAL or Polytite for the membrane joint seal, as listed in Table 4.2.

BEJS is the expansion joint system developed and supplied by EMSEAL to provide a primary watertight seal. The system is comprised of a pre-compressed, silicone and foam hybrid that is installed into field-applied epoxy adhesive on the joint faces. The silicone bellows are locked to the joint faces with a silicone sealant band. The system includes hydrophobic acrylic impregnation in the foam base material to provide low-temperature flexibility.

New Hampshire DOT indicated that their older method of joint replacement required that they break out concrete and install a new concrete header and new knuckle and seal, a process that took two weeks per lane. They now use an elastomeric header material and a strip seal with knuckle and sinusoidal anchors, and can complete the activity in 1 day per lane. They did not provide specific products.

Other Activities

A variety of approaches to speed bridge preservation were provided by individual agencies. These include bridge flushing, spot painting, crack sealing, bridge span replacement, bridge rail sealing, concrete settlement repair, and bridge jacking.

For bridge flushing, Minnesota DOT proposes use of two hose reels on a tanker or a spray bar. They recommend flushing only critical areas including gutter line, curb and rail instead of the full bridge deck. This approach could cut the time in half.

For spot painting, Minnesota DOT recommends using a one coat system. They recommend spot painting at the right time before there is too much corrosion in order to reduce preparation time. This timely spot painting reduces the need for full containment and negative air, which takes days for set up. Use of three coat paint systems requires weeks for painting. The alternate approach could save hours to a day on surface preparation and days on painting when compared to a multiple coat system.

Crack sealing is another very common bridge preservation activity. Minnesota DOT described use of Paulco 2501 Fast Set or TK-9000 for bridge crack sealing. Paulco 2501 Fast Set, manufactured by Viking Paints, Inc., is a two component epoxy that cures rapidly and is designed for use on concrete roads and bridges. TK-9000 is also a two-part epoxy crack filler system that is produced by TK Products Construction Coatings. The material begins to gel in about 25 minutes and is completely hard in four hours, depending on ambient temperatures.

For bridge span replacement, Texas DOT uses Accelerated Bridge Constuction methods. This has reduced the activity time from 96 working days to 31 working days.

Minnesota DOT provided an approach to bridge rail sealing that has improved the activity duration. They use two products: Thoroshene and TriSheen. They indicated that some districts spray apply the products and back roll them, but caution to note mil thickness in doing so. For preparation, they suggested pressure washing instead of sand blasting. However, environmental regulations surrounding water collection and silica exposure may dictate the preparation method that is used.

For concrete settlement repair, the older repair method consisted of mud jacking or slab replacement. If mud jacking is used, larger holes must be drilled in the concrete and time is needed for cement and lime to set before traffic can be returned. Minnesota DOT is using foam jacking, where the material is pumped through small (1/4" to 3/8") drilled holes and the foam sets up in 5 minutes. The time for the settlement repairs has been reduced from 5 weeks to a few days or less.

Minnesota DOT also provided a concept to reduce manpower associated with bridge jacking. They use a unified pump with internal manifold, i.e., there are no feed lines from the pump to the manifold. They are able to utilize one pump for four jacks, reducing manpower and equipment to jack the bridge. In addition, control of the operation is at a single point.

Summary

Chapter 4 has identified products and processes submitted by 11 agencies to speed bridge preservation activities. A few, like bridge span replacement, are clearly beyond the scope of bridge preservation. Most, like joint repair and replacement, deck overlays and deck crack sealing and patching are very common activities.

As mentioned in the introduction to this chapter, agencies were asked to provide products or processes. As a result, many specific products are included in this chapter. It should be noted that the intention is not to endorse specific products, but rather to show some products that other agencies are using with success.

Minnesota DOT provided many ideas for speeding bridge preservation. In addition to products, they identified processes for bridge flushing, spot painting, pourable joint seals, expansion joint gland repair, bridge rail sealing, concrete settlement repair, and bridge jacking.

Chapter 5 includes the survey of Michigan region bridge engineers to react to the national survey's activity life expectancy and construction duration. Chapter 5 also includes the region's bridge activity lists over a 75-year period.

Chapter 5 Survey of Michigan Region Bridge Engineers

The second survey was directed at region bridge engineers in the seven regions of Michigan. They were asked to react to the results of the national survey. For example: did they agree with the life expectancies of the various activities? Did they agree with the durations required to conduct specific bridge activities? In addition, they were asked to show on a timeline specific activities they would do over the 75-year life.

Survey of Michigan Region Bridge Engineers

A region map of Michigan can be found at https://www.michigan.gov/mdot/0,4616,7-151-9615_36946-119648--,00.html. Michigan is a very diverse state and its seven regions include both highly urban (Metro and parts of Grand), and very rural (much of North and all of Superior). The remaining regions, Southwest, University and Bay include both urban and rural, although the cities in these regions are small in relation to Detroit. Michigan is bounded by the Great Lakes and both lakes and rivers are plentiful. The result is a large number of bridges of many types and sizes. In order to develop a tool for calculating the life cycle cost of bridge activities and the user delay costs associated with that program of activities, it was important to get local input into what activities they perform, how long those treatments last, and how long it takes to construct them.

Treatment Life Expectancy

The survey sent to region bridge engineers in each of the Michigan DOT regions asked them to react to the results of the national survey regarding the life expectancy of each bridge activity and the construction duration for that activity. For each activity, a range was provided and the region personnel was asked if they agree. If they did not, they were asked to provide the range they thought was best.

Three examples will demonstrate the results for epoxy crack sealing, epoxy overlay and joint replacement. The result from the national survey for epoxy crack sealing was a life expectancy of 3 to 20 years, with an average of 8.67 years. Four of the regions disagreed with the national survey, with both Southwest and University giving a range of 3 to 10 years, while Superior provided a range of 1 to 9 years. For the epoxy overlay, the national survey provided a life expectancy of 5 to 25 years, with an average of 11.7. Three of the regions disagreed and provided ranges that resulted in a slightly lower average: Bay (5 to 16), North (9-11), and Superior (5 to 16). Southwest and University provided ranges that resulted in a higher average life expectancy: Southwest (11-19) and University (14-23). Finally for joint replacement, three of the regions disagreed with the national survey range of 4 to 30 years, with a national average of 13.25. The ranges provided by Bay (9-29), North (18-20) and Southwest (12-29) all resulted in higher life expectancy for these regions. Note that 4 regions agreed with the national survey. A complete table of responses to the life expectancy of the bridge activities is shown in Table 5.1.

The life expectancy for various bridge activities should provide input into development of a program of activities over the life of a bridge. If the life expectancy of a joint replacement is 15 years, then another joint replacement should be expected 15 years following the first joint replacement. One way that this

| Activity | Nat' l survey lowest low | Nat' l survey highest high | Nat' l Survey Average | Bay | Grand | Metro | North | Southwest | Superior | University |
|--------------------|--------------------------|----------------------------|-----------------------|---------|-------|--------|--------|-----------|----------|------------|
| Approach joints | 1.0 | 15.0 | 7.87 | 1.0-7.0 | | 1-7 | 1.0-<5 | 1-10 | | 3-15 |
| Joint repair | 1.0 | 20.0 | 7.44 | 1.0-7.0 | | 1-10 | 1.0-<5 | 1-7 | 1-10 | 1-10 |
| Deck crack seal | 3.0 | 20.0 | 8.67 | 1.0-7.0 | | | 3 | 3-10 | 1-7 | 3-10 |
| Epoxy inject crack | 10 | 30 | 16.11 | | | | | | | |
| Healer Sealer | 3.0 | 30.0 | 12.70 | <5-11 | | <5-7.5 | | <5-11 | <5-7.5 | 8.5-10 |
| Coat fascia | 3 | 15 | 8.12 | | | | 1-<5 | 3-10 | | |
| Coat substructure | 4 | 20 | 11 | 4.5-16 | | | | | | |
| Coat beams | 5 | 20 | 13.90 | | | | | | | |
| Seal caps | 4 | 15 | 8.43 | | | | | | | |
| Metal mesh panel | No res | No res | No res | | | | | | | |
| Spot painting | 4 | 20 | 9.33 | | | | 6-8 | <3-10 | | 4.5-13 |

| Activity | Nat' l survey lowest low | Nat' l survey highest high | Nat' l Survey Average | Bay | Grand | Metro | North | Southwest | Superior | University |
|-----------------------|---------------------------------|-----------------------------------|------------------------------|------------|--------------|--------------|--------------|------------------|-----------------|-------------------|
| Super. wash | 1 | 5 | 1.89 | 2-3 | | | | | | 1-2 |
| Deck wash | 1 | 5 | 1.89 | 2-3 | | | | | | |
| Drain clean repair | 1 | 2 | 1.60 | | | | | | | |
| Clean bearings | 1 | 30 | 14.58 | | | | | <5-17.5 | | 11.5-29 |
| Lube. bearing | 5 | 20 | 11.25 | | | | | | | |
| Level bridge approach | 8 | 30 | 10.60 | 9- >30 | | 24-27 | 10 | 4.5-10 | | |
| Barrier railing | 5 | 30 | 16.67 | | | | <12 | | | |
| Thrie beam retro | 2 | 35 | 18.56 | | | | | 9-31.5 | | |
| Deck patch partial | 2 | 20 | 9.09 | | | | 13-15 | | | 4.5-11.5 |
| Deck patch full | 5 | 25 | 12.81 | | | | 9-11 | | | 6-11.5 |
| Patch sup. spill5 | 5 | 40 | 13.71 | | | | | 6-9.5 | | 6-17.5 |

| Activity | Nat' l survey lowest low | Nat' l survey highest high | Nat' l Survey Average | Bay | Grand | Metro | North | Southwest | Superior | University |
|--------------------|---------------------------------|-----------------------------------|------------------------------|------------|--------------|--------------|--------------|------------------|-----------------|-------------------|
| Minor sub patch | 1 | 30 | 10.57 | | | | | 5-9.5 | | 5-19 |
| Joint replacement | 4 | 30 | 13.25 | 9-29 | | | 18-20 | 12-29 | | |
| Epoxy overlay | 5 | 25 | 11.71 | 5-16 | | | 9-11 | 11-19 | 5-16 | 14-23 |
| HMA OL w/ WPM | 10 | 30 | 15.55 | <5-12 | | | | <5-8 | | <5-8 |
| HMA OL wo WPM | 2 | 15 | 9.5 | 2.5-7 | | | | 2.5-7 | | 2.5-7 |
| Paint complete | 14 | 40 | 25.06 | | 44-47 | | <20 | | | |
| Paint zone | 3 | 25 | 11.56 | | | | 6-8 | 4.5-19 | | |
| Pin & Hanger | 15 | 50 | 28.75 | 31->50 | | | | | | |
| Barrier rail repl. | 10 | 45 | 27.08 | | | | | | | |
| Bearing replace | 5 | 30 | 22.66 | <8->50 | | | | 16-30 | | 16-33.5 |
| Drain System rep. | 15 | 50 | 24.38 | 15-27 | | | | | | |

| Activity | Nat' l survey lowest low | Nat' l survey highest high | Nat' l Survey Average | Bay | Grand | Metro | North | Southwest | Superior | University |
|-------------------|---------------------------------|-----------------------------------|------------------------------|------------|--------------|--------------|--------------|------------------|-----------------|-------------------|
| Approach slab rep | 7 | 40 | 25.20 | | | | | | | 12-42 |
| Deep concrete OL | 5 | 60 | 24.55 | 11.5-26 | | | 8-9 | 11.5-25.5 | | >15-29 |
| Major sub repair | 10 | 60 | 28.18 | | | | | 16-32 | | |
| Super. repairs | 10 | 30 | 20.0 | | | | | | | |
| Sub. replacement | 25 | 100 | 66.7 | | | | 76-80 | 33-73 | | 28->65 |
| Deck replacement | 15 | 75 | 36.56 | 31->50 | | 21->50 | 40-43 | 24-49 | | 31->50 |
| Super. replace. | 25 | 75 | 52.5 | 53->65 | | | | 48->65 | | 48->65 |
| Bridge replace. | 40 | 100 | 70.36 | | | | 48-78 | | | 63-78 |

Table 5:1 Region Expectations for Activity Service Lives. Note that activity names are abbreviated.

occurs is in conjunction with a deck replacement. Nevertheless, some activity sequences do not match well with the life expectancies from the national and regional surveys.

Activity Construction Duration

In a similar manner as was used for life expectancy, the regions were asked to react to the results of the national survey with regard to activity duration. As shown in Table 3.3, a range of durations for moderate traffic levels and for high traffic levels were obtained from the national survey.

Table 5.2 shows the national survey results and the Michigan region modifications for those activities where the regions disagreed with the national durations. In general, they agreed with the majority of the activity durations. Of the 15 activities that received comments on the duration, 11 were commented by a single region. Three activities had duration modifications from two regions, and only 1 activity (Epoxy Overlay) had comments from 3 regions. The ranges shown in the notes section of the table show that the regions that commented generally feel that some activities can be constructed faster than the construction durations from the national survey.

Region Bridge Activity Lists

Perhaps the most significant feature of the survey of Michigan region bridge engineers was the list of bridge activities that each region would do over a 75-year period. These timelines and activity lists form the basis for calculating both the Bridge Activity Costs (BAC) considering the timed value of money and the User Delay Costs (UDC).

In the instructions for this portion of the survey we state: “Michigan DOT has a timeline for when treatments should be conducted on a bridge. We understand that you are not always able to meet those recommendations due to budgets and priorities. For each category of bridge size below, please insert the treatments when you would most likely do them.” Space was provided for up to five treatments in a year. The instructions included a list of all bridge activities from the national survey but stated that not all activities must be included. In other words, we asked for the list of work that they normally do.

In the survey, space was provided for a variety of bridge configurations: two lanes with two directions of traffic, three lanes, 4 lanes with two lanes in each direction, etc. Region personnel had the option of supplying different lists for each category or a single list for all bridges. Only Grand and Metro regions provided multiple lists, and they each provided two. Table 5.3 shows the 75-year activity timelines for Bay, North, Southwest, Superior and University regions, and these timelines are used for all bridges in those regions in the tool to be presented in Chapter 6. Table 5.4 shows the 75-year activity lists for Grand and Metro regions, with each having two lists. In reviewing Tables 5.3 and 5.4, notice that unused spaces were removed. The regions could list up to five activities in each year. For many years, there were no activities by most of the regions.

| Activity | Duration of Activity from National Survey-Moderate AADT | Duration of Activity from National Survey-High AADT | Michigan Notes |
|-------------------------------|--|--|---|
| Healer Sealer | 1.8 to 5.2 days | 1.1 to 3.0 days | Bay region (2-5 days) for both traffic levels |
| Coat concrete barrier/fascia | 2.8-7.2 days | 5.4 to 15.2 days | Bay region (1-2 days) for both traffic levels |
| Coat Concrete Beams | 3.5 to 9.3 days | 8.4 to 24.2 days | Bay region (2-5) for moderate; (5-10) for high |
| Metal Mesh Panels | No responses | No responses | Southwest region (1-2) days |
| Clean and Reset Bearings | 2.1 to 5.6 days | 3.0 to 8.1 days | Grand region (10-15 days) for high traffic |
| Bridge Barrier Railing Repair | 0.9 to 2.2 days | 1.6 to 4.6 days | Bay region (2-5 days) for both traffic levels; Grand (5-10 days) for high traffic. |
| Deck Patching-partial depth | 2.1 to 5.8 days | 2.0 to 5.4 days | Bay region (5-10 days) for both traffic levels. |
| Deck Patching-full depth | 3.5 to 8.9 days | 6.1 to 17.8 days | Bay region (5-10 days) for both traffic levels. |
| Epoxy Overlay | 5.6 to 27.1 days | 7.1 to 20.1 days | Bay (5-10 days) for both; Grand (1-2 days) for moderate; University (2-5 days) for moderate, (5-10 days) for high |
| HMA overlay with WPM | 9.8 to 29.2 days | 10.2 to 30 days | Bay (2-5 days) for moderate; (5-10 days) for high; University (1-2 days) for moderate; (2-5 days) for high |
| HMA overlay without WPM | 10.2 to 30.5 days | 10.3 to 31.0 days | Bay (2-5 days) for both; University (1-2 days) for moderate; (2-5 days) for high. |

| Activity | Duration of Activity from National Survey-Moderate AADT | Duration of Activity from National Survey-High AADT | Michigan Notes |
|----------------------------|---|---|--|
| Pin and Hanger Replacement | 33.4 to 74.3 days | 31.8 to 72.5 days | University (0.5 to 1 month) for moderate; (1-3 months) for high |
| Bridge Railing Replacement | 25.3 to 60.4 days | 27.8 to 80.0 days | Grand region (5-10 days) for moderate |
| Approach Slab Replacement | 25.0 to 57.1 days | 24.4 to 57.5 days | Grand region (10-15 days) for moderate. |
| Superstructure Repairs | 30.5 to 68.4 days | 32.6 to 80.0 days | University region: (0.5 to 1 month) for moderate; (1-3 months) for high. |

*Table 5:2 Durations for Activities where Regions Offered Changes to National Survey Results.
Note that WPM is waterproofing membrane*

| Treatment Timelines by Region | | | | | |
|-------------------------------|-----|-----------------------|-----------|-----------------------|---------------------------------|
| Year | Bay | North | Southwest | Superior | University |
| 1 | | | | | Approach pavement relief joints |
| 2 | | Epoxy overlay | | Deck Crack Sealing | |
| 2 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 4 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 5 | | Joint sealing/repair | | Healer sealer | Healer sealer, |
| 5 | | | | Joint sealing/repair | Joint sealing/repair |
| 6 | | Deck cleaning/washing | | Deck cleaning/washing | |

| Treatment Timelines by Region | | | | | |
|-------------------------------|-----------------------------------|-----------------------------|----------------------|---------------------------|-----------------------------|
| Year | Bay | North | Southwest | Superior | University |
| 8 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 9 | | | Joint sealing/repair | | |
| 9 | | | Healer sealer | | |
| 10 | Healer sealer | Joint sealing/repair | | Healer sealer | Joint sealing/repair |
| 10 | | Deck cleaning/washing | | Drain system clean/repair | |
| 10 | | | | Joint sealing/repair | |
| 12 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 14 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 15 | Epoxy overlay | Deck patching-partial depth | | Healer sealer | Joint sealing/repair |
| 15 | Joint sealing/repair | Joint sealing/repair | | Joint sealing/repair | |
| 15 | Coat concrete beams | | | | |
| 15 | Deck patching-partial depth | | | | |
| 16 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 18 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 20 | Coat concrete barrier/deck fascia | Joint sealing/repair | Joint replacement J | Healer sealer | Deck patching-partial depth |
| 20 | Coat concrete substructure | Deck cleaning/washing | Epoxy Overlay | Joint sealing/repair | Epoxy overlay |

| Treatment Timelines by Region | | | | | |
|-------------------------------|-------------------------------|-------------------------------|-----------|-------------------------------|-----------------------------|
| Year | Bay | North | Southwest | Superior | University |
| 20 | Joint replacement | | | Deck cleaning/washing | Joint replacement |
| 20 | | | | Deck patching-partial depth | Minor substructure patching |
| 21 | | | | Level bridge approach | |
| 21 | | | | Drain system clean/repair | |
| 22 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 24 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 25 | | Joint replacement | | Healer sealer | Joint sealing/repair |
| 25 | | Epoxy overlay | | Joint replacement | |
| 26 | | Joint sealing/repair | | Deck cleaning/washing | |
| 26 | | Deck cleaning/washing | | | |
| 28 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 30 | Bridge barrier railing repair | Bridge barrier railing repair | | Healer sealer | Joint sealing/repair |
| 30 | Level bridge approach | Level bridge approach | | Joint sealing/repair | |
| 30 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 30 | | Joint sealing/repair | | Bridge barrier railing repair | |

| Treatment Timelines by Region | | | | | |
|-------------------------------|-------------------------------------|-------------------------------------|--------------------------|--------------------------------|-----------------------------------|
| Year | Bay | North | Southwest | Superior | University |
| 31 | | | | Drain system clean/repair | |
| 32 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 34 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 35 | Paint-complete | Joint sealing/repair | | Healer sealer | Joint sealing/repair |
| 36 | | | | Joint sealing/repair | |
| 36 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 38 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 40 | | Paint-complete | Deep concrete overlay | Deep concrete overlay | Deep concrete overlay |
| 40 | Patch superstructure spalling | Minor substructure patching | Joint replacement | Superstructure repairs | Superstructure repairs |
| 40 | Approach slab replacement | Patch superstructure spalling | Paint-complete | Minor substructure patching | Minor substructure patching |
| 40 | | Approach slab replacement | Minor sub. patching | Paint-complete | |
| 41 | | | | Approach slab replacement | |
| 42 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 44 | | Deck cleaning/washing | | Deck cleaning/washing | |

| Treatment Timelines by Region | | | | | |
|-------------------------------|---------------------------|-------------------------------|----------------------|---------------------------|----------------------|
| Year | Bay | North | Southwest | Superior | University |
| 45 | | Bridge barrier railing repair | | Healer sealer | Joint sealing/repair |
| 45 | | Joint sealing/repair | | | |
| 46 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 48 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 50 | Deep concrete overlay | Deep concrete overlay | Epoxy Overlay | Deck cleaning/washing | Joint sealing/repair |
| 50 | Deck patching-full depth | Deck patching-full depth | Joint sealing/repair | | Epoxy Overlay |
| 50 | Bearing replacement | Bearing replacement | | | |
| 50 | Major substructure repair | Major substructure repair | | | |
| 51 | | | | Drain system clean/repair | |
| 52 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 52 | | Epoxy Overlay | | | |
| 53 | | Joint sealing/repair | | | |
| 54 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 55 | | | | Healer sealer | Joint sealing/repair |
| 55 | | | | Major substructure repair | |

| Treatment Timelines by Region | | | | | |
|-------------------------------|----------------------|-----------------------------|-----------|-------------------------------|-------------------------|
| Year | Bay | North | Southwest | Superior | University |
| 55 | | | | Bridge barrier railing repair | |
| 56 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 56 | | | | Patch superstructure spalling | |
| 58 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 60 | Deck replacement | Deck cleaning/washing | | Healer sealer | Deck replacement |
| 60 | | Deck patching-partial depth | | Joint sealing/repair | Substructure Patching |
| 60 | | Joint sealing/repair | | Deck cleaning/washing | Superstructure Patching |
| 60 | | | | Paint-zone | |
| 61 | | | | Drain system clean/repair | |
| 61 | | | | Deck patching-partial depth | |
| 62 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 64 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 65 | HMA overlay with WPM | Joint sealing/repair | | Healer sealer | Joint sealing/repair |
| 65 | | | | Bridge barrier railing repair | |
| 65 | | | | Deck patching-partial depth | |

| Treatment Timelines by Region | | | | | |
|-------------------------------|--------------------|-----------------------|----------------------|---------------------------|----------------------|
| Year | Bay | North | Southwest | Superior | University |
| 66 | | Deck cleaning/washing | | Joint sealing/repair | |
| 66 | | | | Deck cleaning/washing | |
| 68 | | Deck cleaning/washing | | Deck cleaning/washing | |
| 69 | | | | Joint sealing/repair | |
| 70 | | Paint-zone | Paint-complete | Deck replacement | Joint sealing/repair |
| 70 | | Deck replacement | Minor sub. patching | Deck cleaning/washing | |
| 70 | | | Deck replacement | Approach slab replacement | |
| 71 | | | | Drain system clean/repair | |
| 72 | | Deck cleaning/washing | | | |
| 72 | | Epoxy overlay | | Deck cleaning/washing | |
| 75 | Bridge replacement | Salvage value | Epoxy Overlay | Salvage value | Epoxy overlay |
| 75 | | | Joint sealing/repair | | Joint sealing/repair |

Table 5:3 Activity lists over 75-year Period for Regions having one Activity List for All Bridge Categories. Gray tinting is provided at 5-year intervals as a visual aid only.

| Treatment Timelines for Grand and Metro Regions | | | | |
|---|---------------|---------|---------------------------------|---------------------------------|
| Year | Grand 1 | Grand 2 | Metro 1 | Metro 2 |
| 1 | | | Approach pavement relief joints | Approach pavement relief joints |
| 5 | Healer sealer | | | |

| Treatment Timelines for Grand and Metro Regions | | | | |
|--|-----------------------------------|-----------------------------------|-----------------------------|--------------------------------|
| Year | Grand 1 | Grand 2 | Metro 1 | Metro 2 |
| 10 | | | Healer sealer | Healer sealer |
| 10 | | | Deck Crack Sealing | Deck Crack Sealing |
| 15 | Deck patching-partial depth | Deck patching-partial depth | | Deck patching-partial depth |
| 15 | Epoxy overlay | Epoxy overlay | | |
| 15 | Joint replacement | Joint replacement | | |
| 15 | Coat concrete barrier/deck fascia | Coat concrete barrier/deck fascia | | |
| 15 | Coat concrete substructure | Coat concrete substructure | | |
| 16 | Coat concrete beams | Coat concrete beams | | |
| 20 | | | Healer sealer | Epoxy overlay |
| 20 | | | Level bridge approach | Level bridge approach |
| 20 | | | Spot painting | Spot painting |
| 20 | | | Deck patching-partial depth | Deck patching-full depth |
| 25 | | Deep concrete overlay | | Seal abutments and caps |
| 25 | | Approach slab replacement | | Bridge barrier railing replace |
| 25 | | Minor substructure patching | | Superstructure repairs |
| 25 | | Paint-zone | | |
| 25 | | Superstructure repairs | | |
| 26 | | Joint replacement | | |
| 26 | | Coat concrete barrier/deck fascia | | |
| 26 | | Coat concrete substructure | | |

| Treatment Timelines for Grand and Metro Regions | | | | |
|--|-----------------------------------|-----------------------------------|----------------------------|----------------------------|
| Year | Grand 1 | Grand 2 | Metro 1 | Metro 2 |
| 26 | | Coat concrete beams | | |
| 30 | Deep concrete overlay | | Seal abutments and caps | Deep concrete overlay |
| 30 | Approach slab replacement | | Superstructure repairs | |
| 30 | Minor substructure patching | | Epoxy overlay | |
| 30 | Paint-zone | | | |
| 30 | Superstructure repairs | | | |
| 31 | Joint replacement | | | |
| 31 | Coat concrete barrier/deck fascia | | | |
| 31 | Coat concrete substructure | | | |
| 31 | Coat concrete beams | | | |
| 40 | | | | Healer sealer |
| 50 | | Deck replacement | Deck replacement | Deck replacement |
| 50 | | Paint-complete | Superstructure replacement | Superstructure replacement |
| 50 | | Approach slab replacement | Paint-complete | Paint-complete |
| 50 | | Major substructure repair | Approach slab replacement | Approach slab replacement |
| 50 | | Superstructure repairs | | Seal abutments and caps |
| 51 | | Joint replacement | | |
| 51 | | Coat concrete barrier/deck fascia | | |
| 51 | | Coat concrete substructure | | |
| 51 | | Coat concrete beams | | |

| Treatment Timelines for Grand and Metro Regions | | | | |
|--|-----------------------------------|--------------------|--------------------|-------------------------|
| Year | Grand 1 | Grand 2 | Metro 1 | Metro 2 |
| 55 | Deck replacement | | | |
| 55 | Paint-complete | | | |
| 55 | Approach slab replacement | | | |
| 55 | Major substructure repair | | | |
| 55 | Superstructure repairs | | | |
| 55 | Joint replacement | | | |
| 56 | Coat concrete barrier/deck fascia | | | |
| 56 | Coat concrete substructure | | | |
| 56 | Coat concrete beams | | | |
| 60 | | | | Healer sealer |
| 65 | | | | Seal abutments and caps |
| 75+ | HMA overlay with no membrane | Bridge replacement | Bridge replacement | Bridge replacement |

Table 5:4 Activities and Timing for Grand and Metro Regions, Each with Two Activity Lists

Observations from the Activity Lists

There were significant differences in the activity lists submitted by the various regions. Some of these differences are easily explained but others are more indicative of philosophies and different priorities. In evaluating the lists, one thing is critical: the bridge condition at various points over the 75-year period are not equivalent.

Bay region began their activities in year 10 with a healer sealer and had multiple preservation activities in year 15 and year 20. Joint replacement was to be done in year 20. Other notable activities were painting-complete in year 35, a deep concrete overlay in year 50, deck replacement in year 60, an HMA overlay with waterproofing membrane in year 65. In general, Bay region scheduled activities every five years early in the bridge life and every 10 years later in the bridge life.

North and Superior regions had common practices with regard to bridge activities. Both included deck cleaning and washing every two years. Both included joint sealing and repair

every five years. North region applied an epoxy overlay in years 2, 25, 52 and 72. North region anticipated joint replacement at year 25, and deck replacement at year 70. Painting-complete and substructure and superstructure repairs were scheduled for year 40. Superior region applied healer sealer at five-year intervals beginning at year 5. Like North region, joint replacement was listed in year 25, and deck replacement at year 70. Year 40 included a deep concrete overlay, substructure repairs and superstructure repairs. A salvage value, equal to ¼ the cost of bridge replacement, is included in year 75 to account for the 100-year bridge replacement time set for North and Superior regions.

University region's activity list included joint sealing and repair every five years, with joint replacement at year 20 and in conjunction with deck replacement at year 60. Healer sealer was applied in year 5, an epoxy overlay in year 20 and year 50, and a deep concrete overlay in year 40. Another epoxy overlay in year 75 may be used to extend the bridge service beyond 75 years.

Southwest region planned to apply a healer sealer and conduct joint sealing and repair in year 9. The next activity was joint replacement and an epoxy overlay in year 20. A second joint replacement along with a deep concrete overlay and painting-complete was listed in year 40, followed by an epoxy overlay and joint sealing and repair in year 50 and again in year 75. Deck replacement and painting-complete was identified for year 70. Southwest region had the longest periods between activities of any of the region activity lists.

Both Grand and Metro regions provided two activity lists: one for bridges up to 4 lanes in width and one for larger structures. Grand 1 and Metro 1 apply for bridges up to 4 lanes in width and Grand 2 and Metro 2 apply to wider bridges. The activity lists for Grand and Metro regions are shown in Table 5.4. While most of the other regions conducted activities at 5 and 10 year intervals, Grand region has activities in year 15, 30, and 55 in the Grand 1 list. The Grand 2 activity intervals were 15, 25/26, and 50/51 years. At each of these treatment periods, multiple activities are anticipated. Joint replacements are scheduled at each interval. Deck treatments include Epoxy overlay at year 15, a deep concrete overlay at the next interval, followed by deck replacement at the final interval prior to bridge replacement in year 75. Grand region uses zone painting at the 25 or 30-year activity interval, followed by painting-complete at 50 or 55-year interval.

Metro region had activities at 10-year intervals up through 30 years, with some repair activities on larger bridges at year 25. For smaller bridges, they used healer sealer at 10-year intervals with an epoxy overlay at year 30 and deck replacement at year 50. For larger structures, they used a healer sealer at year 10, 40, and 60; an epoxy overlay in year 20, and a deep concrete overlay in year 30. Deck replacement for both Metro 1 and Metro 2 is scheduled in year 50, along with paint-complete and other activities.

Table 5.5 shows the number and percentage of regions using each of the bridge activities. The table shows that all the regions use epoxy overlays and 86% use deck replacement and partial-depth concrete repairs. Other dominant bridge activities include deep concrete overlays, paint-complete and joint replacement, all listed by 71% of regions.

Chapter 7 includes case studies that compare the activity lists impact on present worth costs and user delay costs over the 75-year life for area single bridge using the activity lists of five different regions. By using a single bridge for this case study, the variations due to bridge deck area and speed limit are eliminated. In evaluating the activity lists and the resultant life cycle cost analysis and user delay costs, it is important to keep in mind that there is no assurance that the various activity lists result in the same bridge conditions over the life of the structure.

Summary

Chapter 5 has described a Michigan-only survey which asked region bridge engineers to react to the results of the national survey with regard to life expectancy and construction durations of bridge activities. In general, Michigan region bridge engineers agreed with the national survey regarding construction durations of most activities. This survey also asked for activities and timelines over a 75-year period.

This information forms the basis for the life cycle cost analysis and user delay cost calculations, which are described in Chapter 6. Chapter 6 also outlines an Excel-based tool to calculate discounted bridge activity costs (BAC) and User Delay Costs (UDC) associated with those activities over the 75-year period.

| Activity | # of regions | % of regions |
|------------------------------------|---------------------|---------------------|
| Approach pavement relief joints | 2 | 28.57 |
| Joint sealing/repair | 4 | 57.14 |
| Deck Crack Sealing | 2 | 28.57 |
| Epoxy Inject Superstructure Cracks | 1 | 14.29 |
| Healer sealer | 5 | 71.43 |
| Coat concrete barrier/deck fascia | 2 | 28.57 |
| Coat concrete substructure | 2 | 28.57 |
| Coat concrete beams | 2 | 28.57 |
| Seal abutments and caps | 1 | 14.29 |
| Spot painting | 2 | 28.57 |
| Deck cleaning/washing | 1 | 14.29 |
| Drain system clean/repair | 2 | 28.57 |
| Lubricate bearing and seat | 1 | 14.29 |
| Level bridge approach | 3 | 42.86 |
| Bridge barrier railing repair | 2 | 28.57 |
| Deck patching-partial depth | 6 | 85.71 |
| Deck patching-full depth | 4 | 57.14 |

| Activity | # of regions | % of regions |
|---|---------------------|---------------------|
| Patch superstructure spalling | 3 | 42.86 |
| Minor substructure patching | 4 | 57.14 |
| Joint replacement | 5 | 71.43 |
| Epoxy overlay | 7 | 100.00 |
| HMA overlay with waterproofing membrane | 3 | 42.86 |
| HMA overlay with no membrane | 2 | 28.57 |
| Paint-complete | 5 | 71.43 |
| Paint-zone | 3 | 42.86 |
| Pin & hanger replacement | 2 | 28.57 |
| Bridge barrier railing replace | 1 | 14.29 |
| Bearing replacement | 1 | 14.29 |
| Approach slab replacement | 4 | 57.14 |
| Deep concrete overlay | 5 | 71.43 |
| Major substructure repair | 4 | 57.14 |
| Superstructure repairs | 4 | 57.14 |
| Deck replacement | 6 | 85.71 |
| Superstructure replacement | 2 | 28.57 |
| Bridge replacement | 4 | 57.14 |

Table 5:5 Number and Percentage of Regions Listing each Activity

Chapter 6 Life Cycle of Activity Costs and User Delay Costs

One of the goals of this project was development of a tool to assist region bridge engineers in considering both life cycle cost of a program of activities and the impact of those activities on bridge users. This tool combines the results of the national and Michigan-only surveys with engineering economic analysis and calculation of user delay times and costs. The tool is Excel based and consists of a series of macros in visual basic for applications (VBA). This approach was selected because most engineers are familiar with Excel and have easy access to it. This chapter will begin with a brief overview of the calculations of activity costs considering the time value of money and the user delay costs. The bridge traffic table that contains much of the traffic and bridge information used in the calculations will be presented. The tool will then be described: input, present worth analysis of bridge activity costs (BAC), User delay cost (UDC) calculations, and output.

Life Cycle Cost Analysis

Engineering economic analysis allows a cost at any point in time to be considered as an equivalent cost at some other point in time, either in the future or at the present. It also allows calculation of an equivalent series of equal amounts over a set period of time. The Federal Highway Administration describes this process as follows:

“Life-Cycle Cost Analysis (LCCA) is an economic analysis that is used to evaluate the total cost of an investment option over its entire life (Walls and Smith 1998). Using an economic analysis technique known as “discounting,” all projected costs are converted into present dollars and summed to produce a net present value (NPV) or net present cost (NPC). If multiple alternatives with similar benefits are being considered over identical analysis periods, the net present values or costs can be compared to determine which alternative is the most cost effective.”

For example, if a project is expected to cost \$200,000 in five years, the value of that future expenditure at the present time (time zero) is the present worth (PW) and is calculated with the formula: $PW = \$200,000 * \{1/(1 + dr)^5\}$, where “dr” is the discount rate. Tables of the bracketed portion of this equation can be found in standard textbooks on engineering economic analysis for a wide range of times and discount rates. In generalized form:

$$PW = Cost * \left\{ \left(\frac{1}{(1+dr)^n} \right) \right\} \quad \text{Equation 6.1}$$

Where n is the year of at which the cost is incurred and dr is the discount rate.

Alternatively, engineering economic analysis allows calculation of an equivalent series of equal annual amounts (EAC), or a single amount at some time in the future (FW). The tool developed in this project used present worth analysis for the entire series of activity costs as well as user delay costs over the 75-year analysis period.

The discount rate is set by agency policy or practice, usually in the area of pavement type selection. Again, the Federal Highway Administration describes the discount rate as follows:

“The discount rate, which represents the combined effects of interest and inflation rates, is used to estimate the present value of all future costs. It should be selected to reflect both historical trends over long time periods and near-term projections. FHWA recommends that highway agencies use OMB Circular A-94, Appendix C in selecting a discount rate.

The choice of discount rate is very important; thus it is useful to understand the impact of discount rate on LCCA. Higher discount rates reduce the present value of future costs by a greater amount than do lower discount rates; a zero discount rate values future costs the same as current costs; and negative discount rates increase the present value of future costs above those of current costs.”

OMB Circular A-94 Appendix C shows a 2017 interest rate on Treasury Notes and Bonds with a 30-year term at 2.8 percent and recommends use of the 30-year term value for analysis periods longer than 30 years. The tool developed in this project requires that the user input the discount rate. A range of 0.005 to .05 is accepted. Three percent was used in the case studies in Chapter 7.

Each activity in the 75-year analysis period was converted to an activity cost using results from the National Cooperative Highway Research Program (NCHRP) as identified in Chapter 2. The costs used in this analysis are intended to be relative rather than absolute. They will not equal total project costs as estimated by Michigan DOT but will produce nationally appropriate costs in relation to other common bridge activities.

User Delay Costs

The number of users impacted by each activity depends on the average annual daily traffic at a time considered to be the present, the percentage of commercial vehicles, the percentage of automobile and other non-commercial traffic, the growth rate of that segment of traffic and the duration of the particular activity.

The input for average daily traffic for commercial and non-commercial vehicles is included in the bridge/traffic database. This database also includes growth rates for both traffic classes as well as other information that is used in the tool developed in this project. Calculation of the future traffic is based on the formula (Equation 6.2) for calculating future worth in engineering economics:

$$FT = PT(1 + gr)^n. \quad \text{Equation 6.2}$$

Where ***FT*** is future traffic, ***PT*** is present traffic, ***gr*** is the traffic growth rate, and ***n*** is the year.

Traffic volumes vary by the time of day. For example, rush hour traffic in more suburban or urban areas will extend from 6 am until 9 am and in the afternoon, from 4 pm until 7 pm. Commercial trucking in some areas may increase overnight, and frequently commercial drivers

will try to avoid rush hour traffic. The average hourly traffic distribution for Michigan was used to convert the average daily traffic to the average hourly traffic.

User delay is affected by roadway capacity, which is a function of speed limit. Total road capacity is also a function of the number of lanes, but in the tool, capacity is expressed in vehicles per hour per lane. The tool uses three levels of capacity: 2100 if the speed limit is greater than or equal to 65, 1600 for speed limits greater than 44 and less than 65, and 1300 for speeds less than or equal to 44. Note that the capacity of a bridge with all lanes open to traffic is always higher than that of the same bridge but with lane closures to accommodate work activities. In general, traffic slows due to work in progress, even if it doesn't stop.

A queue forms when traffic slows due to limited capacity. Traffic in the queue continues to move, but at a reduced (often greatly reduced) speed. As a result, there are two components to work zone delay: The delay of reduced speed to pass through the work zone, and the queue delay prior to the work zone. It is important to note that once a queue forms, it may continue even after the traffic distribution results in "below capacity" conditions because remnants of the queue are carried over into subsequent hours until the queue is fully dissipated.

Another component of the user delay calculation is the value of time for both automobile traffic and commercial vehicles. For purposes of the tool, all commercial vehicle travel is considered to be business related. It includes a weighted average value of wages for drivers of uni-body trucks and tractor trailers and includes the weighted average vehicle occupancy. Automobiles and other light traffic are considered at 50% of the weighted average value, again considered the weighted average vehicle occupancy. As referenced in Chapter 2, all values of wages and vehicle occupancy for each class are based on Michigan-specific data from the most recent sources.

Bridge-Traffic Table

A Bridge Traffic Table was created for the project by the Co-Principal Investigator, Dr. Tim Gates. This table is structured to allow the user to select a bridge of interest (BOI), after which the macro instructions will look up and present to the user many input variables associated with the BOI. This approach reduces the need for user data inputs and the likelihood of input errors. This section will describe the features of the Bridge Traffic table. Table 6.1 shows the columns and column headings for the Bridge Traffic table, and values from the table for Bridge #421 to demonstrate typical values.

For a specific BOI, the user only needs to input its Structure Number (StrcNum) found in column A. Excel's LOOKUP function requirement that candidate numbers be sorted in ascending order results in a region's bridges being separated throughout the table. To make it easier for region personnel to find a specific BOI, there is a separate page for each region, listing only structures from their region.

| Column | Heading | Example Bridge # 421 |
|--------|---------|----------------------|
| A | StrcNum | 421 |
| B | FID | 666 |

| Column | Heading | Example Bridge # 421 |
|--------|----------------------------|----------------------|
| C | MSU | 667 |
| D | Facility | US-23 |
| E | ReRegion | Bay |
| F | County | Arenac |
| G | Urban | Rural |
| H | SpeedLimit | 70 |
| I | Highway_Type1 | Freeway |
| J | Highway_Type2 | Freeway - Two Lane |
| K | AADT_2017 | 3,110 |
| L | AADT_AVG | 2,822 |
| M | AADT_Growth_AnnualAverage | 5.79% |
| N | CAADT_2016 | 150 |
| O | CAADT_AVG | 173 |
| P | PERC_COMM_AVG | 6.27% |
| Q | CAADT_Growth_AnnualAverage | -6.58% |
| R | BRKey | 06106111000S020 |
| S | StrcNum | 421 |
| T | DeckArea | 11930 |

Table 6:1 Bridge Traffic Table Fields and Example for Bridge #421

There are three other bridge numbers in the Bridge-Traffic Table. Column B contains a Federal Identification Number (FID) beginning at zero and extending through one less than the total number of Michigan structures on the federal aid system. Column C contains the number assigned by Michigan State University (MSU). This number equals the FID plus one. The third column from the right (column R) contains the Bridge Key (BRKey), an alpha-numeric field, which makes it difficult to use in Excel LOOKUP functions. While the tool can identify the BOI based on only the StrcNum, we recommend using the BRKey to confirm that the selected structure is correct.

Other identifying information is included in the table. This includes the facility (route number) (column D), region (column E), and county (column F). This identifying information will be included in the output page. The MDOT region determines which of the activity lists will be used in the analysis. The column labeled Urban (column G) indicates whether the BOI is located in a rural or urban environment. The posted speed limit in miles per hour is given in the speed limit column (column H). This speed limit is used to calculate the capacity and the work zone speed.

The next two columns of the table (columns I and J) are Highway_Type 1 and Highway_Type 2. The Highway_Type 2 entry for the BOI is tested to extract the number of lanes from the text string and convert it to a numeric value. This number varies between one and six, with one being for bridges on ramps. The most common structures are two-lane bridges. Three-lane bridges are largely confined to the Metro, Grand, University, and Southwest Regions.

The total traffic is listed in the next three columns. The average annual daily traffic includes total daily traffic for both automobiles and trucks. The 2017 values are in column K, followed by the AADT_AVG (column L). The overall traffic growth rate is in column M. Following those total daily traffic columns are four columns for commercial vehicles. The first of the commercial traffic columns indicates the daily average number of trucks in 2016 (column N), followed by the average number of commercial vehicles per day (column O). The percent commercial vehicles is shown in column P, with the growth rate for commercial vehicles in column Q. While most of the growth figures in the table are useful, growth rates of ten percent or higher per year would not be sustainable without increasing road and bridge capacity.

Column T is the Deck Area in square feet. This is used in the tool to calculate total costs from unit costs.

Overview of Tool1

The basic parts of the bridge preservation tool consist of input of the bridge of interest, look up of bridge characteristics in the bridge traffic table, calculation of activity costs for the BOI, input of the discount rate, calculation of the PW of the activity list, calculation of the PW of user delay costs, and output.

The analysis tool consists of the following twelve macros:

| Macro Name | Function |
|-------------------|---|
| Capacity | Calculates lane capacity based on speed limit |
| AAA | Computes queue length |
| BBB | Work zone delay and queue delay and total delay time and value |
| Definevariables | Calls other subroutines; input bridge identification number |
| Lanes2 | Reads highway type alphabetic string and extracts numeric number of lanes |
| Activities | Selects activity list for the region of the BOI |
| Costs | Calculates activity cost based on deck area, number of lanes |
| Discrate | Input discount rate between 0.005 and .05 |
| Preswth | Calculates present worth of bridge activity costs |
| ActivityDuration | Looks up duration for each activity in the 75-year analysis period |
| Usercost | Calculates user delay cost (calls macro subroutines AAA and BBB) |
| UsercostSummation | Calculates cumulative user delay cost. |

Table 6:2 Names and Functions of the Macros in Analysis Tool1

The tool's user only needs to enter two values: the StrcNum and the discount rate. The StrcNum is input immediately upon starting an analysis. The user should select a StrcNum from the region page. Note that not every consecutive number is assigned, so it is important to look up the number and verify the route information. Information on the region pages can be sorted if that makes finding the BOI easier. For example, the region page could be sorted by county. The

discount rate is entered by the user after the BOI characteristics have been obtained from the data.

Four tables are included in the tool: Bridge Traffic Table, Activity Lists for each region, Durations and Costs for the Bridge Activities, and the Hourly Traffic Distribution Table. A separate bridge traffic table is included for each region to facilitate identifying the bridge of interest. Activity lists include one list for each region for Bay, North, Southwest, Superior, and University Regions. Two activity lists are included for Grand and Metro Regions. All of the activity lists are from the Michigan survey of region bridge engineers.

The bridge traffic table provides much of the information needed to proceed with the analysis. Most of the lookup activities are conducted from the main bridge traffic table, which includes all regions and StrcNum in ascending order. This “master table” should not be sorted as doing so will interfere with the lookup functions in Excel.

Present Worth of Work Activities or Bridge Activity Cost (BAC)

From the bridge traffic table, the following items are used in preparing to calculate the BAC of the activity lists: Region, deck area, highway type 2. The number of lanes is extracted from the highway type 2 field. Additional information is identified and shown on the output page: County, route number and the date are included to assist the user with record keeping. The speed limit, number of lanes, and initial AADT are included on the output page and are used in the calculation of User Delay Costs.

The Region obtained from the bridge traffic table is used to select the appropriate list of activities over the 75-year analysis period for both BAC and UDC. The activity lists are in columns B through J of the worksheet “Activities”. The activity list for the BOI is copied into column K.

Worksheet “Durations and Costs” includes a list of all bridge activities in column A and estimated total cost per lane per span in column B. The unit costs in column B are from NCHRP but can be easily modified to Michigan specific costs. Based on the number of lanes and estimated number of spans, the total activity cost for the BOI is calculated and recorded in column C. The cost associated with each activity in the 75-year period is obtained from this table and input into the Activities worksheet in column L.

As already mentioned, the user inputs the discount rate to be used in the calculation of both BAC and UDC. The discounted values are highly dependent on discount rate. An example with a single bridge and four discount rates ranging from 2.5% to 4% is included in Chapter 7. In general, an agency will select a discount rate to be used in pavement type selection and that discount rate should be used in this analysis. Agencies should review and update their discount rates periodically to reflect recent trends in the prices of treasury bonds and other financial instruments.

The discounted cost of each activity is calculated using the PW formula shown earlier. The cumulative PW of activity costs, (BAC) is shown in column M of the Activities worksheet. The final net present value of all work activities (BAC) is transferred to the output page.

User Delay Cost Calculations

Calculation of user delays associated with bridge activities is complicated. It begins with the current average annual daily traffic and current commercial average daily traffic, which increases over time using the annual growth rate. The values for the BOI are obtained from the bridge traffic table.

The distribution of traffic during the 24-hour day is not uniform. Traffic tends to be heaviest during morning and evening rush hours and to be lower during late night hours. The average distribution for Michigan was used and a graph showing the distribution is presented in Figure 6.1. This graph shows traffic beginning to increase at 5 am, but significantly increasing at 6 am and remaining high throughout the day. Traffic begins to decline at 3 pm, and significantly declines after 4 pm.

Why is the daily traffic distribution important? A number of activities, including some bridge preservation activities, take a portion of a day to complete. The number of people impacted depends on the time of day or night when the work is accomplished. In urban areas, the work may be required to be done at night, while in rural areas, daytime work is acceptable. For longer duration activities, a lane closure will remain in place. Even in this case, the hourly distribution will be used, because traffic may slow during the heavier traffic periods and form a queue, but that queue will dissipate overnight when traffic is reduced.

The flow of traffic is also affected by road capacity. Capacity is the number of vehicles per hour that can pass through a segment without slowing. If traffic exceeds the capacity, then traffic slows and a queue develops. Capacity is highly sensitive to speed limit, which is available in column H of the bridge-traffic table. Three capacity levels are included in the analysis tool: 2,100 vehicles per hour for speeds greater than or equal to 65 mph, 1,600 vehicles per hour for speeds greater than 44 mph and less than 65 mph, and 1,300 for speeds less than or equal to 44 mph. An example illustrating the impact of speed limit on three bridges of similar size is included in Chapter 7.

Even when a queue does not form, the speed of traffic in work zones tends to decrease slightly and this delay extends from the beginning of traffic control prior to the bridge until the end of traffic control after the bridge. Five mph was used for this modest decrease in speed and one mile was used as the workzone length.

The total traffic delay for a vehicle is the sum of the vehicle delay due to the existence of the workzone and the vehicle delay due to a queue if one exists.

For each activity in the activity list, the duration of the work activity is obtained, based on traffic level, from columns F or G of the “Durations and Costs” worksheet. Values in column F are for moderate traffic levels and those in column G are for high traffic volumes. Based on the good agreement of region bridge engineers with the activity durations from the national survey, the values in this table are from the national survey. If a region wishes to change a duration, they can substitute a local value for a specific activity in the appropriate column. It is recommended

to copy the original table below the existing table prior to making any substitutions so the original values can be retrieved.

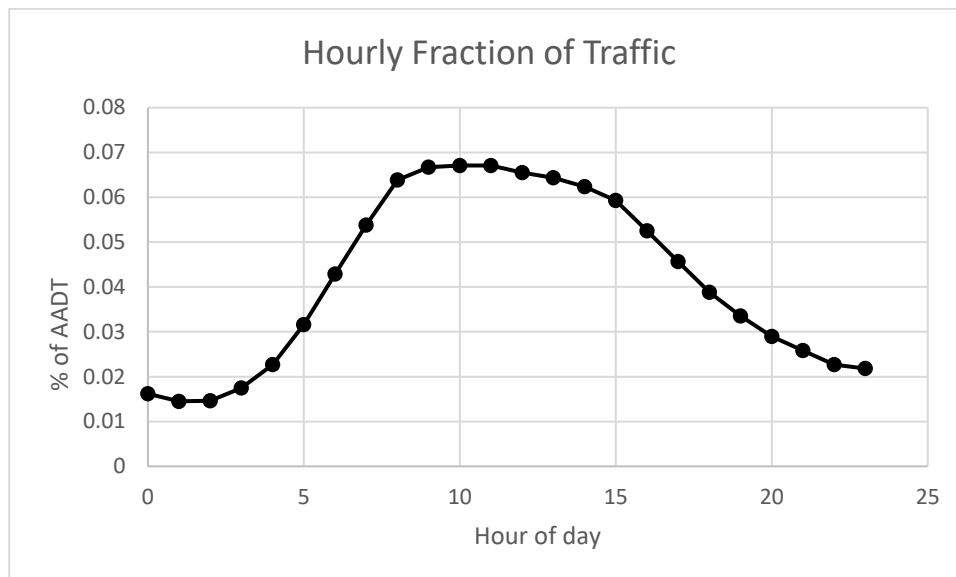


Figure 6-1 Hourly distribution of traffic, using Michigan average distribution

Based on the duration and whether a bridge is classified as urban or rural, an expected time for conducting the work is identified. For activities with durations of 15 days or less, one hour is allotted for traffic control set up at the beginning of the day's operation and one hour for traffic control removal at the end of the work period. Daytime work commences at 9 am and ends at 4 pm. Of this time, five hours is actually spent conducting the activity. Nighttime work commences at 8 pm and ends at 6 am, with eight hours spent conducting the bridge activity.

Work activities with durations less than 5 days are assumed to be done during the day. When the duration is between 5 and 15 days, work will be conducted at night for urban locations and during the day in rural locations. If the duration is longer than 15 days, it is assumed that traffic control will remain in place throughout the construction duration.

For each activity, and for each hour of traffic during the conduct of that activity, the traffic level is calculated, the number of vehicles delayed due to the work zone, and the number of vehicles delayed due to queue formation or dissipation is calculated. The total vehicles are then distributed between automobiles or other light vehicles and commercial vehicles and the number of persons delayed is based on Michigan vehicle occupancy statistics for each class. The value of the delay time is based on 50% of the value of time for automobiles and 100% of time for commercial vehicles, using Michigan statistics for those values as indicated in Chapter 2. User delay costs are calculated by summing over the time period to complete the activity. The discounted value of the user delay costs is calculated using the discount rate. The cumulative total user delay cost is summed over the full 75-year analysis period. The total discounted user delay cost is transferred to the output page.

Appendix A includes definitions of all variables used in the analysis. Appendix B contains a flow chart of the tool, while Appendix C contains the VBA (Visual Basic for Applications) code.

Summary

Analysis Tool1 was developed as part of this project to allow a bridge manager to estimate the PW of the activity list for their region with the user delay costs associated with that list. The tool is Excel-based and consists of twelve macros. User input is limited to the bridge identification number and the discount rate.

The tool selects the activity list from the region containing the BOI, calculates the cost of those activities, has the user input a discount rate, and calculates the Present Worth of the 75-year list of activities. The tool then looks up the duration of each of the activities, uses discounting to calculate the traffic in the year of the activity, and calculates both work zone delay and queue delay for that activity. This is done for each activity in the series. The delay is converted into monetary value using 50% for the portion of the traffic that is automobiles and 100% valuation for the commercial vehicle portion. Total user delay cost is calculated and discounted to time zero and a cumulative total user delay cost is included in the output page.

Chapter 7 includes several examples that show the sensitivity of the calculations to variables including deck area, speed limit, region (for a single bridge using various region activity lists) and discount rate. Four of the activity lists were modified: in three cases, they include more preservation activities and in one, the activity list is simplified. The method for doing this is illustrated in Chapter 7.

Chapter 7 Examples Using Tool1

An Excel-based tool has been developed that allows region bridge engineers to consider both life cycle cost of a program of activities and the impact of those activities on bridge users. Tool1 was described in Chapter 6. In this chapter, the tool will be used to consider a variety of items that influence decisions or that impact the discounted bridge activity cost (BAC) or the User Delay Cost (UDC) calculations. As indicated in Chapter 6, the user is only required to input the bridge identification number (StrcNum) and the discount rate. With the exception of Example 1, a discount rate of three percent was used for all examples.

Example 1: Impact of Discount Rate on BAC and UDC

As was described in Chapter 6, the bridge activity costs and the user delay costs are discounted using the discount rate. In the tool, present worth analysis is used, so discounting moves future costs to a time considered to be the present. The tool accepts discount rates between 0.005 and 0.05. Error messages are provided if a discount rate is either outside that range or if none is provided.

The discount rate is used in life cycle cost analysis for pavement type selection by many state agencies. The same discount rate as is used in pavement type selection should be used for the tool.

To demonstrate the influence of discount rate on BAC and UDC, two bridges were selected. Bridge 99 is in Allegan County, Grand region. The AADT is 8,180 vehicles per day with 9.7% commercial vehicles. The deck area is 1463 square meters and the speed limit is 70 miles per hour. Bridge 399 is located in Arenac County, Bay region. The AADT is 5370 vehicles per day with 7.3% commercial vehicles. The deck area is significantly smaller: 821 square meters. The speed limit is 55 miles per hour. The lower speed for Bridge 399 results in a reduction of capacity from 2100 to 1600 vehicles per hour. Bridge 99 is in an urban location, while bridge 399 is rural. In addition, the two regions have different activity lists.

The analysis tool was run for each of these bridges for five values of discount rate: 0.02, 0.025, 0.03, 0.035, and 0.04. Figure 7.1 is a graph of BAC and UDC for both bridges. The figure shows that UDC are higher than BAC or discounted activity costs for both bridges. It is significantly higher for Bridge 99 in Grand Region. As the discount rate increases, the impact of future expenditures is increasingly diminished, especially for expenses further in the future.

The ratio of BAC of activity costs to UDC was dramatically different for these two structures. For Bay region, structure 399, the ratio ranged from 0.77 at 2 percent discount rate to 0.57 at 4 percent discount rate. For Grand region, structure 99, the ratio ranged from 0.16 at 2 percent discount rate to 0.17 at 4 percent discount rate. As expected, the urban bridge had much higher UDC than did the rural bridge: for example, at a discount rate of 0.02, the values of UDC were about \$1.04 million dollars for the Grand region bridge compared to \$0.31 million dollars for the Bay region bridge. The BAC of the activity costs was also higher for the Grand region bridge and the ratio of the BAC's was a function of discount rate. That ratio of BAC of Bay to BAC of Grand was 146% at a discount rate of 2 percent and decreased to 114% at a discount rate of 4 percent.

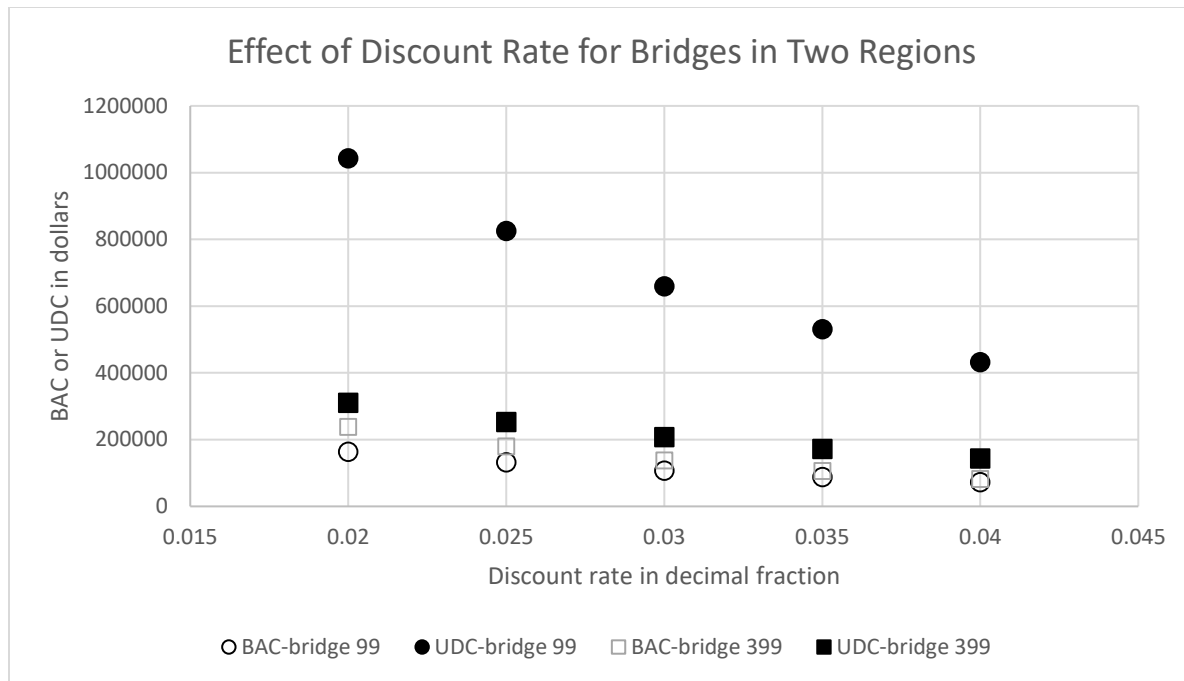


Figure 7-1 Impact of Discount Rate on Discounted Bridge Activity Costs and User Delay Costs for Two Bridges in Two Regions.

Example 2: Impact of Speed Limit for a Single Bridge in University Region

Bridge 1875 in Clinton County, University region was selected to demonstrate the impact of vehicle speed on BAC and UDC. The initial average daily traffic was 17672 vehicles per day and the analysis traffic growth rate was 2.16%. The deck area was 10,205 square feet. The University region activity list was used for all five speed limits. This approach to evaluating the impact of speed limit required sequentially changing the value in the “traffic db” worksheet.

Since all the cases involved the same activity list and the same deck area, the BAC was constant for all cases at \$205,673. When the speed limit is lowered, the number of vehicles able to pass a point is reduced. That is, capacity is reduced from 2,100 vehicles per hour at 70 miles per hour to 1,300 vehicles per hour for the roadway with a speed limit of 35 miles per hour. The reduced traffic capacity results in increased queuing, which increases user delay time. It should be noted that most of the low speed limit routes in the “traffic db worksheet” are in urban areas, which further impacts working times and user delays. UDC increase as the speed limit decreases, as shown in Figure 7.2.

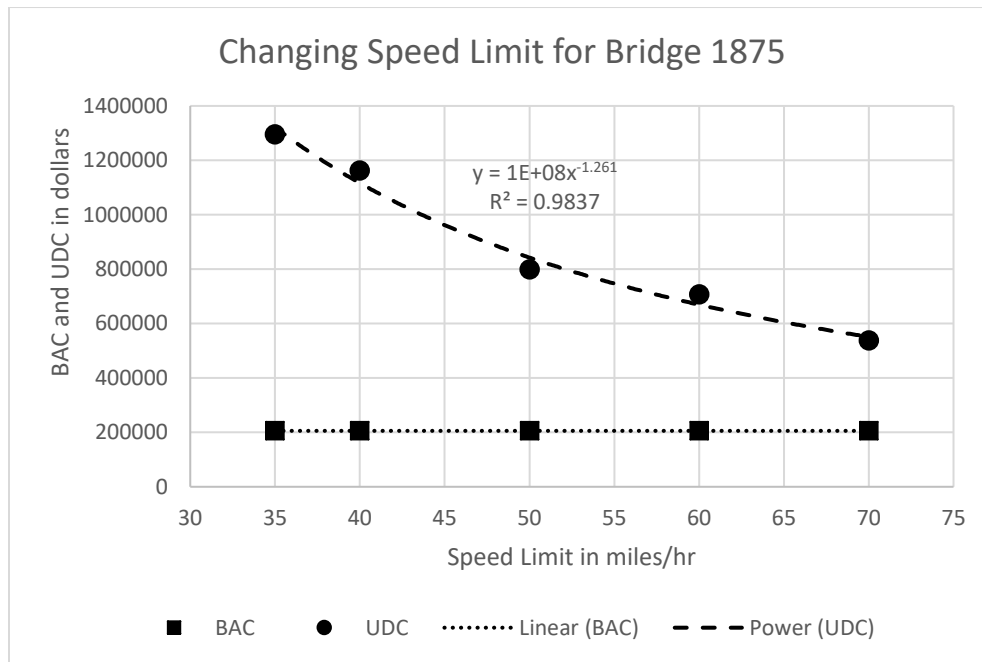


Figure 7-2 Effect of Speed Limit on BAC and UDC for Bridge 1875 in University Region.

Example 3: Impact of Average Daily Traffic for Bridge 607 in Bay Region

Bridge 607 in Bay Region was used to demonstrate the impact of average daily traffic on BAC and UDC. This structure has a deck area of 7995 square feet, and actual initial traffic of 13,994 vehicles per day with traffic growth rate of 2.03%. Traffic levels were varied between 9000 and 24000 vehicles per day. This required sequentially modifying the traffic level in the “traff db” worksheet.

In all four cases, the bridge was subjected to the same Bay region activity list, so the BAC remained constant at \$249,739.

UDC increased with increasing traffic level, as shown in Figure 4, more than quadrupling between 9000 and 24000 vehicles per day. The ratio of BAC to UDC varied between 0.76 for the lowest average daily traffic to 0.17 for the highest traffic level. In this case, the BAC is lower than the UDC for all traffic levels.

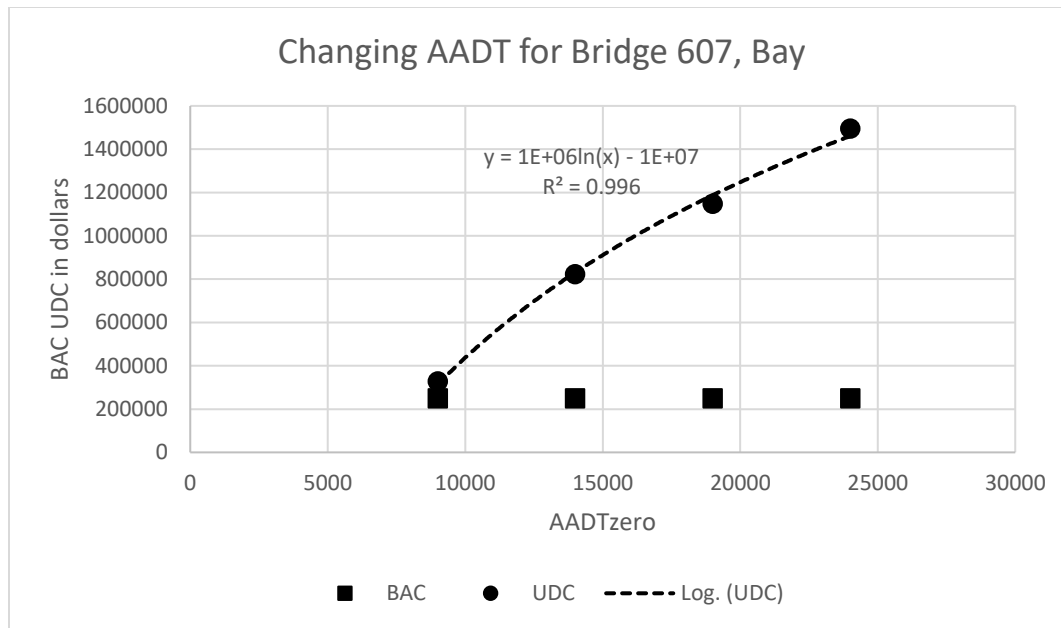


Figure 7-3 Impact of Average Daily Traffic on Activity Costs and User Delay Costs for Bridge 607 in Bay Region.

Example 4: Using Different Region Activity Lists for the Same Bridge

It should be clear from the preceding examples that many variables impact the BAC and the UDC. With that said, it is interesting to apply other region activity lists to the same bridge to visualize the impact of the lists on BAC and UDC. Regions that opt for more activities that are of shorter duration will generally have lower BAC and UDC. Of course, if there are many short activities, there will be an increase in both BAC and UDC.

Bridge 612, located in Bay County, Bay Region, was selected for this example. It has a deck area of 7995 square feet, initial traffic level of 13,994 vehicles per day with a traffic growth rate of 2.03%. It has 5.92% commercial vehicles. The speed limit is 70 mph and the bridge is two lanes wide.

The results of the analysis of for six regional activity lists is shown in Figure 7.4. The BACs range from \$161,132 for University to \$297,176 for Superior. UDCs ranged from \$379,540 for University to \$1.26 million for Grand region.

Figure 7.4 also reflects the effects of the very different activity lists. All of the activity lists are shown in Chapter 5. As stated in Chapter 5, the activity lists do not necessarily result in comparable bridge conditions over the 75-year period but do represent the regions' current thinking on which activities they will use and when.

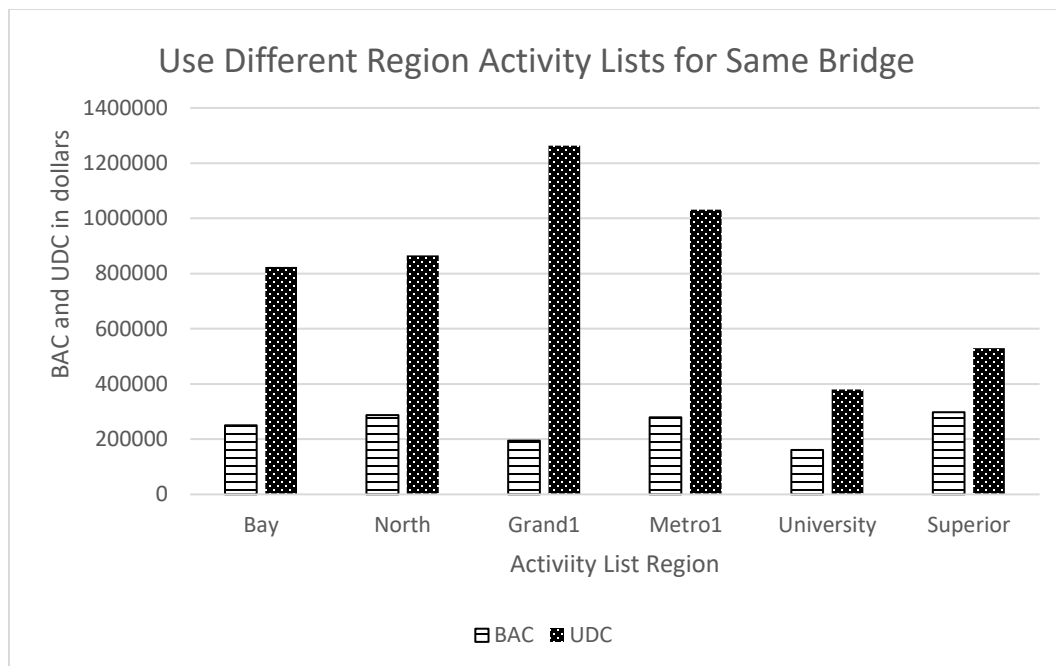


Figure 7-4 Comparison of Use of Different Region Activity Lists for a Single Bridge

Example 5: Altered Activity Lists

Activity lists for four regions were altered to evaluate the impact of changing the list on BAC and UDC. In each case, the adjustments will be described and the results of the analysis for the original activity list and the modified list will be compared.

The Bay region's activity list was adjusted as follows:

- Joint sealing and repair was added to healer sealer in years 10 and 16.
- Epoxy overlay and joint replacement was moved from year 22 to year 25.
- Epoxy overlay and joint sealing and repair was moved from year 32 to year 35.
- Deep concrete overlay in year 42 was coupled with joint replacement in year 45.
- Healer sealer in years 50 and 61 were moved to years 55 and 63.
- Epoxy overlay in year 67 was moved to year 69.

All of the adjustments to the Bay region's activity list were limited to very common bridge preservation activities and each adjustment other than the first bullet item involved a small timing change of 3 to 5 years. Other activities in the Bay activity list remained as identified by the region.

Bay region bridge 612 was analyzed using both the original list and the altered list. Bridge 652 has an average daily traffic of about 14,000 vehicles per day, with 5.92% commercial vehicles and a deck area of 7995 square feet. Using the altered activity list decreased the BAC from \$249,739 to \$231,708, a decrease of 7.2 percent. UDCs decreased with the altered activity list from \$823,544 to \$788,413, a decrease of 4.3 percent.

University region's activity list made use of joint seal/repair at 5-year increments throughout much of the 75-year analysis period. Adjustments to the University region's activity list included the following

- Healer sealer was added in year 15.
- Epoxy overlay with joint replacement was moved from year 20 to year 25.
- An epoxy overlay was added in year 40.
- The deep concrete overlay with joint replacement was moved from year 40 to year 50, eliminating the epoxy overlay in year 50.
- Healer sealer was added in years 61 and 70.
- All other activities were retained.

A University region bridge was analyzed with both the original activity list and the modified activity list. Bridge 1856 has an average daily traffic of about 20,500 vehicles per day and a deck area of 6847 square meters. The BAC changed from \$137,995 to \$130,670 in going from the original list to the modified list. UDCs increased 42 percent, from \$798,016 to \$1,135,985. It is important to note that in the modification of this activity list, additional treatments were added, yet the PW of the activity costs went down. This is because some of the more expensive activities were pushed out by 5 to 10 years.

North region's activity list contained deck cleaning every second year and joint seal repair every five years. Their activity list was modified to eliminate the deck cleaning and reduce the joint seal repair. These changes resulted in earlier deck replacement and bridge replacement at year 75. The BAC for the original list was \$241,197, while that for the modified list was \$134,418. The original list UDC was \$392,321, while the modified list UDC was \$395,050. As has been mentioned earlier, it is important to note that the activity lists do not produce equal bridge condition over time.

The activity list for Superior, similar to that of North region, includes bridge deck washing every two years, joint sealing repair every five years. Healer sealer is used on a five-year cycle to prolong bridge deck life. The modified activity list for Superior region includes more bridge barrier rail repair, approach slab leveling and pushes out healer sealer by two years. Bridge 5938 was used to illustrate the effect of changing from the original activity list to the modified activity list. The bridge is located in Mackinac county, is two lanes wide and carries about 2,500 vehicles per day. The deck area is 8752 square feet. Using the modified activity list resulted in a decrease in BAC from \$325,314 to \$287,057. The UDC increased from \$146,653 for the original list to \$189,750 for the modified list.

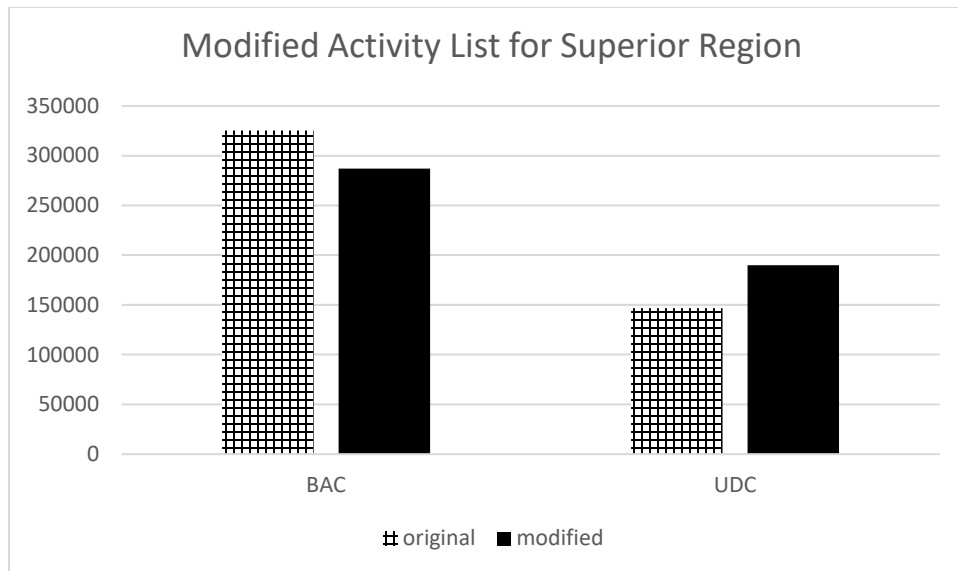


Figure 7-5 Impact of modified activity list on BAC and UDC for Superior Region

How to Modify an Activity List

As has been demonstrated with four examples, modification of an activity list can result in decreased activity costs with modest increases in user delay costs, increases in both BAC and UDC, or decreases in both BAC and UDC. The focus needs to be on creating a list that maintains bridge condition without unduly interrupting the travelling public.

Worksheet “Alternate acts” is designed to allow a user to modify an activity list. The blue columns are the original region activity list and these should not be altered. Immediately next to the region’s blue column is a column where the user can put in a modified list. Make sure to include activities over the full 75-year period. Once the modified list is completed, copy the list and paste it into the worksheet “Activities” under the correct region. Note that when you do this, you are erasing the original list, but that list can be retrieved using the blue columns.

One analysis that might be useful would be to sequentially use other region’s activity lists for a bridge of interest in your region. This would require copying the blue highlighted list of activities from each region into the modified activity list and copying it into the “activities” sheet. The alternate activity lists originally shown in the “Alternate acts” worksheet can also be copied and used by other regions if they think that list of activities may result in overall better bridge conditions.

Use the same discount rate for both original and altered activity lists to see the impact of the changes on BAC and UDC.

One other type of modification may be done. If a region has experience that their activity list results in bridge replacement occurring later than 75 years, a salvage value can be added in year 75 instead of “bridge replacement”. The salvage value represents the remaining value of the bridge at 75 years. That salvage value must be added to the worksheet “Durations and Costs” and if the expected life in years is EL, the Salvage value is equal to:

$$\text{Salvage Value} = \left(\frac{(EL - 75)}{EL} \right) * \text{Bridge Replacement Cost}$$

The entry for salvage value currently in the worksheet is for an expected life of 100 years. This expression can be modified to accommodate other expected lives by modifying cell B39. The salvage value has a negative sign and reduces the BAC. There is no UDC associated with the salvage value.

Summary

The examples in this chapter demonstrate the impact of several key variables on BAC and UDC in Tool1. Increasing the discount rate resulted in lower BAC and UDC. Setting the discount rate is usually a policy decision made as part of an agency's pavement type selection process.

Traffic speed was shown to impact capacity, with lower speeds resulting in larger user delays and UDC. Lane capacity ranges from 2,100 vehicles per hour for speeds greater than 65 miles per hour to 1,300 vehicles per hour for speeds less than 45 miles per hour. The traffic speed for a structure to be analyzed is included in the bridge traffic table.

Increasing traffic level, or AADT, resulted in increased user delay costs for a single bridge tested at varying traffic levels. Because a single bridge in one region was used, the BAC was constant.

Comparisons can be made across regions but need to be done with care. An example used six different activity lists for a single bridge and showed the impact of the activity lists on both BAC and UDC.

The final example showed the impact of modifying the activity lists of four regions. In each case, the modified BAC was lower than the original BAC but the UDC decreased in the cases of Southwest region and Superior region, stayed nearly the same for North region, and increased for University region. The amount of change depends on the specific activities and their timing as well as the traffic level, bridge size and discount rate.

Chapter 8 Preservation/No Preservation Tool

A second analysis tool (Tool2) has been developed that also calculates the discounted activity costs and user delay costs. This tool considers two options for a single bridge of interest: one case includes capital maintenance bridge preservation activities, and the other the case with no preservation. For the no preservation case, joints are replaced at 25 and 50 years and the bridge deck is replaced at 50 years. An RFA at 75 years triggers the bridge replacement at 80 years.

The preservation case includes the following activities:

1. Joint sealing/repair
2. Deck patching-partial depth
3. Joint replacement
4. Epoxy overlay
5. Hot mixed Asphalt overlay with waterproofing membrane
6. Deep concrete overlay
7. Deck replacement
8. Bridge replacement.

For the preservation option, joint replacement still occurs at approximately 20 year intervals, but the time between deck replacements is greatly extended by use of the other preservation treatments. This include epoxy overlay, asphalt overlay with waterproofing membrane and deep concrete overlay. The timing of the preservation activities was set collaboratively with Michigan DOT personnel to assure the list of activities would be acceptable.

The other key feature of this analysis tool is that the user provides the bridge age. If a bridge is, say, 9 years old, the analysis makes all activities up to and including 9 years as blank, and the analysis considers all activities from the bridge age plus one through the analysis period. The tool is best suited to bridges that are just approaching the first anticipated treatments with preservation at about 10 years but can be used for bridges up to 79 years old.

If a bridge is significantly older, say 49 years old, the program logic works the same way. All activities from 0 through 49 are blank and the analysis begins with activities in year 50. The logic will work, but caution is required. A bridge that is 50 years old may be in very acceptable condition if it has been well-maintained. But it can also be in very poor condition. The analysis only compares preservation versus no preservation and the user of the tool needs to assure that the bridge they are investigating is in sufficiently good condition that preservation remains an option. Otherwise a rehabilitation or reconstruction option should be undertaken.

One of the important facts about Tool2 is that the preservation activity list extends to 105 years, while the no preservation case has bridge reconstruction at 80 years. In order to accommodate this difference, an equivalent annual cost is calculated for each activity list using its' analysis period. The equivalent annual cost is a term from engineering economic analysis in which a series of monetary values are converted into a uniform annual amount based on the discount rate.

The duration of the no preservation case was extended to 105 years by using the first 25 years of treatments. This approach allows evaluation of bridges up to 79 years old. The output page for

the preservation versus no preservation tool includes the Equivalent Annual Cost of the Bridge Activity Costs and the Equivalent Annual Cost of the User Delay Costs. Because of the different analysis periods, it is not appropriate to make decisions based on BAC or UDC.

Preservation-No Preservation Tool

The logic and methodology of the tool is outlined in Appendix B. The tool uses the same method to calculate activity cost as was used in Tool 1. In the preservation versus no preservation case, there are two activity lists: one for capital maintenance/preservation activities every 10 to 20 years and the other for no preservation. In the no preservation case, only three activities occur: joint replacement, deck replacement, and bridge replacement. Joint replacement occurs at 25 year and joint and deck replacement occur in year 50. RFA repairs occur in year 75, which triggers the bridge reconstruction in year 80.

In the preservation case, epoxy overlays, asphalt overlay with waterproofing membrane, and thick concrete overlays are used to extend the deck life to 65 years. Joint sealing and repair and partial depth concrete patching are also included. With a new deck constructed at 65 years, a minimum 40-year life for the new bridge brought the time for bridge reconstruction to 105 years. There is also an intermediate preservation treatment after the deck replacement and prior to the bridge reconstruction. Bridge activities for both cases are found on worksheet “pres no pres activities.” They can be changed or modified by the user, but it is recommended to make a copy of the original lists prior to making changes. See the section of Chapter 6 on Modifying Activity Lists for guidance but note that changes for Tool2 will be to worksheet “pres no pres activities.” The lists for both the preservation and the no preservation options were created with input and discussion with Michigan DOT personnel.

The tool requires the user to enter the bridge age. All activities up to and including the bridge age are ignored and the adjusted year (adjyear) begins at 1 at year age+1. The first set of activities for the preservation case are at year 10. If an analysis is being conducted on a bridge that is 9 years old, the adjusted year for the first set of activities would be 1. The adjusted years apply to both the preservation case and the no preservation case. The adjusted year is used in discounting activity and user delay costs.

Calculation and lookup of activity costs and durations uses the same logic as was used in Tool 1. A separate worksheet “pnp costs and durations” was created because of the much shorter list of capital maintenance activities in Tool2.

User costs are calculated using the same logic as was used in Tool1 and is done first for the preservation activity list and then for the no preservation activity list. It is important to note that there are many more activities in the preservation list, but more of them are of short duration.

Output for Tool2 is on the “output pres-nopres” worksheet. This sheet contains the bridge id and the region, county, route, speed limit, deck area, initial average annual daily traffic, number of lanes, the age of the structure and the analysis traffic growth rate. In addition, the user supplied discount rate is included. The output page includes the calculated bridge activity costs and user delay costs for both the preservation list and the no preservation list. In bolded typeface are the equivalent annual costs for both the BAC and UDC for preservation and no preservation lists.

The bold typeface is to remind the user that decisions must be based on equivalent annual cost due to the difference in time to reconstruction for the two activity lists.

Example using Pres-No Pres Tool

Bridge 421 was selected for this example. It is located on US 23 in Bay Region, Arenac County. The deck area is 11930 square feet, and it is a two lane bridge. Posted speed is 70 miles per hour.

Eight different ages between 5 years and 79 years were evaluated. The purpose was to demonstrate the impact of age on the activity costs and the user delay costs. The change in Equivalent annual cost of the bridge activity costs (EAC-BAC) is shown in Figure 8.1.

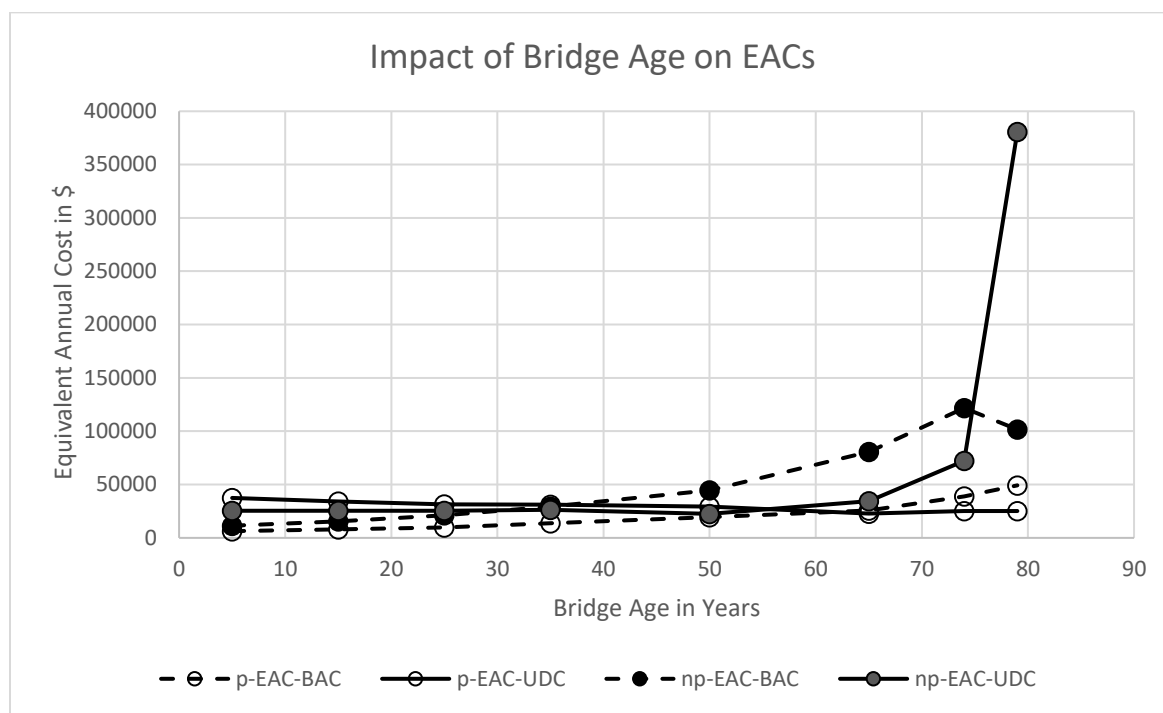


Figure 8-1 Impact of bridge age on equivalent annual cost of bridge activities for Bridge 421 in Bay region

The dashed lines in Figure 8.1 are the equivalent annual costs of the bridge activity lists, with solid points being the no preservation case and unfilled points being the preservation case. In general, the EAC-BACs increase gradually over time. The EAC-BAC for the preservation case is consistently lower than that for the no preservation case. The difference between the two cases increases as bridge age increases, because the bridge reconstruction at year 80 for the no preservation case is discounted over a shorter period than for the preservation case. Note that there is a decline in EAC-BAC for the no preservation case when the age is 79. That is because the emergency repairs at year 75 are no longer included in the activity list.

The EAC-UDC for the preservation case is higher than the no preservation case until around age 55. This is because the preservation case has many activities spread throughout the 105-year analysis period. After bridge age 55, the impact of the emergency repairs at year 75 and the

bridge reconstruction at year 80 significantly impact the no preservation case. The future reconstruction for the preservation case at year 105, is still discounted over 50 years. These impacts are shown in Figure 8.2.

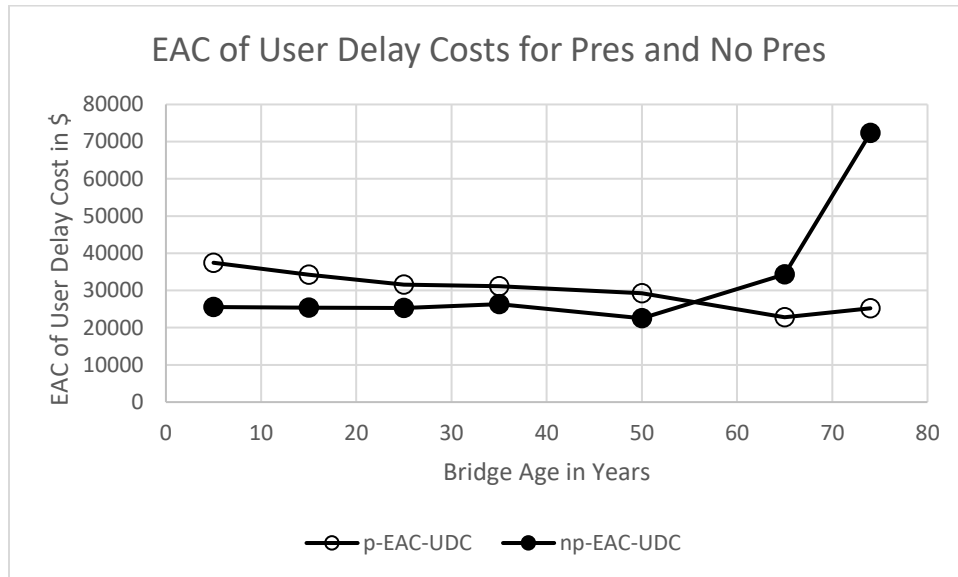


Figure 8-2 Impact of Bridge Age on EAC-UDC for preservation and no preservation cases for Bridge 421 in Bay region.

Summary

Tool2 allows the user to evaluate a bridge of interest using either capital maintenance/preservation activities or no preservation activities. The tool requires the user to enter the StrcNum and the age of the bridge as well as the discount rate. The tool uses Excel's lookup functions to obtain the bridge region, county, route, number of lanes, deck area, speed limit, current average daily traffic.

Total costs for both the preservation activity list and the no preservation list are calculated using logic identical to Tool1. A separate table is provided due to the much shorter list of activities. The total costs are based on the number of lanes and the bridge deck area and are used to calculate the BAC for both the preservation and no preservation cases. UDCs are also calculated for both cases using the same logic as Tool1.

The two activity lists reached bridge reconstruction at different times: 105 years for the preservation case and 80 years for the no preservation case. As a result of this difference, the equivalent annual cost is the appropriate comparison value. Tool2 provides the EAC-BAC and EAC-UDC for both the preservation and the no preservation cases on the worksheet "Output pres-nopres".

An example was included showing the impact of bridge age on EAC-BAC and EAC-UDC for both preservation and no preservation cases.

Chapter 9 Implementation and Conclusions

An Excel-based tool (Tool1) has been developed that allows region bridge engineers in considering both life cycle cost of a program of activities and the impact of those activities on bridge users. The tool was used to evaluate the impact of a number of variables on BAC and UDC: discount rate, speed limit, and average daily traffic. Comparing across regions was demonstrated and the limitations in doing so were described. In addition, modification of the region's activity list was done for four regions and showed that modification can result in reduced PW with limited increase in UDC or significantly increased PW and UDC. This approach was also used to consider the impact of 4 different activity lists on a single bridge. The last section of Chapter 7 provides a procedure for modifying the activity list to consider more or less preservation, or the use of an activity list from another district to evaluate the impact on BAC and UDC.

A second Excel-based tool (Tool2) has been developed that compares equivalent annual costs for preservation and no preservation activity lists. The user enters the bridgeid, bridge age, and the discount rate. The tool calculates BAC and UDC for each of the activity lists, but EAC-BAC and EAC-UDC are used in decision making because the preservation activity list has a time to reconstruction of 105-age, while the no preservation activity list has reconstruction at year 80. An example, showing the impact of changing bridge age from 5 years to 79 years, with a total of 8 ages considered, is provided in Chapter 8.

Implementation

Implementation is the process of moving a new idea, concept or tool from development to routine use. According to the Active Implementation Research Network, "implementation is a process, not an event. The process is marked by stages that have been identified in practice. Implementation in practice takes time and effort. Exploration, installation, initial implementation and full implementation stages..." are involved.

The exploration stage involves identification of needs of research recipients and identification of tools to meet those needs. Exploration should not assume readiness for the tools, but should create readiness. Installation prepares the user to do the new work or the new process. Initial implementation involves a small group of "first implementers" using the tool, identifying improvements and methods that will facilitate use by others. Finally, full implementation is defined by a tool or method being used by 50% of the target audience. Maintaining that 50% utilization is not easy because if a user leaves, it takes a few months for a replacement to be selected, trained, coached and finally to become an established user.

While all of these stages of implementation are more easily applied to medicine and social service research than they are to applied research, it is important to consider them in identifying strategies for implementation of this project. In the exploration portion of implementation of engineering research, the research typically results from a research need that is identified by the funding agency followed by a proposal on how to address the need. The installation process in a state agency largely consists of identifying the target audience for the results of the research and approaches to make them aware of the research results. Initial implementation generally

consists of a small group of potential users becoming familiar with the new tool and identifying improvements or teaching aides to assist others in the target audience. Finally, when 50 percent of the target audience is using the tool, it is considered to be fully implemented.

The target audience for this project consists of bridge management and bridge maintenance engineers, both in central office staff and in the regions. Since Michigan DOT is highly decentralized, decisions are made at the region level with some oversight from central staff. Evidence of this can be found in the very different activity lists from the regions. Central office staff tend to focus on overall statewide bridge conditions, while region personnel make decisions to balance regional bridge conditions, available funds, and citizen expectations.

The goals of this project were two-fold:

1. development of a tool that allows the bridge manager to consider both construction costs and user delay costs
2. identification of processes and products to speed bridge preservation activities.

With the tools developed, it is important to introduce the tool to the target audience and demonstrate its use.

Most engineers are familiar with Excel spreadsheets and will require little training to use the analysis tool. The analyst finds the StrcNum for the bridge of interest either in the bridge traffic table or in the bridge traffic table for their region. The StrcNum is in Column A of either table. A button on the output worksheet is pressed to initiate the analysis, and the StrcNum is requested. The region, county, route, number of lanes, and other information on the structure is filled in automatically. A pop-up box requests the discount rate, after which the BAC and UDC are calculated and included on the output page.

Similarly, to use the preservation versus no preservation tool, the analyst will enter the StrcNum for the bridge of interest, the bridge age, and the discount rate. A button on the “Output pres-nopres” worksheet is pressed to initiate the analysis. The region, county, route, number of lanes, and other information on the structure is filled in automatically. The output from Tool2 is presented on the worksheet “Output pres-nopres,” and includes the EAC-BAC and EAC-UDC for both the preservation and no preservation activity lists.

A webinar could be used to introduce the project and the tools to Michigan DOT bridge engineers. The webinar would be PowerPoint slides with screen shots and other illustrations. That webinar would include the following topics:

- Brief introduction to project
- National survey key findings (activity expected life and construction durations)
- Michigan region bridge activity lists
- BAC and UDC- key concepts and calculations for Tool1
- Bridge traffic table and other key tables
- User supplied inputs (bridge id and discount rate)
- Examples showing the impact of key variables

- Modifying activity lists and comparing with region list
- Tool 2 Preservation versus No preservation
- Questions and answers

It is hoped that the webinar would encourage central office and district personnel to “play with” the tool and explore various changes in their activity list for both BAC and UDC. This would be initial implementation stage. As shown in the examples in Chapter 7, even modest changes in activities over the 75-year analysis period to include lower-cost preservation activities resulted in reduced BAC and may lower or raise UDC, depending on the activity duration and timing. Given that the tool evaluates only a single bridge, having a region modify its activity list, which are applied to a network of bridges, could result in significant cost savings.

A four-page technical brief could also be used to make region bridge engineers aware of the tool, its purpose and some of the results of the surveys and the analysis tool. The content would be similar to the webinar but abbreviated to provide information in a short period of time and also be serve as a handy guide.

Results of the project can also be shared regionally through the Midwest Bridge Preservation partnership. The northeast and southeast partnerships may also be interested due to the participation of some of their member states in the national survey.

A short article could be developed with the products and processes submitted by other states to speed bridge preservation. The intended audience for the article would be bridge maintenance and bridge preservation engineers. It is hoped that additional states beyond those that responded to the national survey might suggest their own methods and products to expand the list over time.

Future Improvements

The methods and products to speed bridge preservation could be maintained and expanded over time. Some of the products have been in use for quite some time, but others are new. It is likely that someone within Michigan is trying a product or process with success. Bringing new products and approaches forward and maintaining that list has value to the agency. A national survey that includes only this topic might get significantly more responses than the much longer national survey reported in this project.

One of the portions of the tool that could be improved is the unit cost table. This table is populated from a national research effort. The costs are not intended to replicate costs from bidding a project, but rather to approximate the total costs for the activity to be placed, that is, including labor, materials and traffic control. Development of unit costs for Michigan DOT, or specific regions within Michigan could be done using contract cost data if the agency wishes more precise BACs.

User delay costs can be expanded to include additional costs associated with delays: increased vehicle operating costs, costs of delayed shipments for commercial deliveries, decreased fuel efficiency, and environmental costs associated with queues of running vehicles, among others. Again, the project sought a reasonable and consistent estimate of the cost of delay to the user and based that on queue time and work zone time.

The analysis tool is based on current data for wages, vehicle occupancy, speed limits and other factors. As bridges are widened or otherwise modified to handle traffic requirements, the bridge traffic table and other tables used in calculating BAC and UDC will become out-of-date and require refreshing.

Two data elements were noted to be problematic: the traffic growth rate and the growth rate for percent commercial vehicles. Traffic growth rates were based on relatively recent traffic counts. Some of the growth rates are very high. When the growth rate is very high and is used over a period of 75 years or more, the results are impractical without significant widening of the structures. For example, if a two lane bridge currently carries an average annual daily traffic of 12,000 vehicles per day, and the growth rate is 5.6 percent, the traffic in year 50 is over 182,000 vehicles per day, and grows to more than 480,000 vehicles per day in year 60. These numbers cannot be supported without constant queuing on a two-lane structure. Some of the commercial vehicle growth rates were also extremely high. A study to evaluate and select appropriate long-term traffic growth rates, both overall and for commercial vehicles, is recommended.

Conclusions

The national survey provided information on the expected performance life of a comprehensive list of bridge activities, and an estimated duration for constructing those activities. The survey showed a growth in the use of contractors to conduct many bridge maintenance activities. The survey of Michigan region bridge engineers generally agreed with the construction durations from the national survey.

Each region submitted a 75-year activity list for a generic bridge. Those activity lists varied from region to region, with the more urbanized regions generally minimizing the number of construction activities. North and Superior regions conducted more preservation activities including bridge washing, joint sealing repair, and deck treatments. University region included joint repair and resealing at almost every 5-year interval. In developing these lists, the region bridge engineers were asked to list what they actually do, so the activity lists give a snapshot of how bridges are being managed in Michigan.

The national survey included a question asking for products or processes used by the agency to speed bridge preservation activities. The most common responses were in the area of joint sealing and joint replacement. Deck sealers are another common area where use of silane products or healer sealers have reduced construction time. Rapid setting and curing deck patching materials were also a common activity for accelerated completion. All responses are included in Chapter 4.

An Excel-based tool, Tool1, was developed that combines the activity list with cost data to obtain the discounted present worth of the construction activities, the bridge activity cost (BAC). The tool also evaluates user delay cost (UDC) based on traffic and the durations of construction. These delay costs are also discounted in the tool. A series of examples demonstrate the impacts of various factors on PW and UDC including the discount rate, speed limit, traffic level and district activity list. A feature that was added to the tool allows the activity list to be modified

and to observe the effect of the modification on BAC and UDC. This aspect of the tool allows the bridge manager to “re-think” their activities and try different strategies.

Since the tool is based on data tables, those tables will require updating to remain current. Other work might be directed at long term traffic growth rates, as use of short-term growth rates results in unreasonably high traffic volumes when extended over a 75-year period. It may also be desirable to consider an even longer bridge life of 100 years.

Similarly, Tool2 was developed to compare activity lists and user delay costs for a single bridge for preservation and no preservation cases. Results are also based on table data, which will require updating to remain current.

Chapter 10 Appendix A: Variable list and Definitions

Variables for Tool 1: Calculation of BAC and UDC

| Variable | Description |
|----------------------|---|
| Aadtzero | Average annual daily traffic at time 0; from traff db |
| | |
| AADT(i) | Average annual daily traffic in Year i (calculated using traffic growth rate.) |
| actcost | Total cost of a bridge activity. Used in calculating discounted activity cost in sub preswth. |
| actcostdb | Table of all total costs for all activities. Used in sub preswth. |
| Activitylists | Range containing all activity lists for all regions |
| Actlist | Activity list for the bridge of interest. |
| Comvehpercent | Percent Commercial Vehicles = (% Single Body Trucks + % Tractor Trailers); from traff db |
| County | County in which bridge of interest is located. Included on Output page. |
| cv | Percent commercial vehicles. From traff db. Includes both single body and tractor trailer trucks. |
| Cumuserdelaycost | Summation of user delay costs for all activities (UDC). Calculated in sub usercostsummation and reported on Output worksheet. |
| Deckarea | Deck area in square feet (from Traff db) |
| Dr | Discount Rate (Decimal Fraction). Range is .005 to 0.5. Input in sub Disctrate. |
| Duract(i,a) | Duration of bridge Activity "a" in Year "iv" (Days) |
| Hightype | Highway type in text field of traff db. Number of lanes is extracted from this text and converted to numeric. |
| hrlydf | Decimal fraction of traffic in each hour |
| hrlytraf(num) | Traffic volume in Hour "num" |
| I, ii, iii, iv, etc. | Counters used in loops. |
| numlanes | Number of lanes on bridge; extracted from hightype |
| County | County in which bridge of interest is located. Included on Output page. |
| cv | Percent commercial vehicles. From traff db. Includes both single body and tractor trailer trucks. |
| Cumuserdelaycost | Summation of user delay costs for all activities (UDC). Calculated in sub usercostsummation and reported on Output worksheet. |
| Deckarea | Deck area in square feet (from Traff db) |
| Dr | Discount Rate (Decimal Fraction). Range is .005 to 0.5. Input in sub Disctrate. |
| Duract(i,a) | Duration of bridge Activity "a" in Year "iv" (Days) |
| Duract(i,a) | Duration of bridge Activity "a" in Year "iv" (Days) |
| Hightype | Highway type in text field of traff db. Number of lanes is extracted from this text and converted to numeric. |
| hrlydf | Decimal fraction of traffic in each hour |
| hrlytraf(num) | Traffic volume in Hour "num" |
| I, ii, iii, iv, etc. | Counters used in loops. |
| numlanes | Number of lanes on bridge; extracted from hightype |

| | |
|--------------------|--|
| num | Hour of day when work is being performed (Ranges 1 to 24) Day work: $(09 \leq \text{num} \leq 16)$ Night work: $(01 \leq \text{num} \leq 06 \text{ OR } 20 \leq \text{num} \leq 24)$ |
| Numdays | Number of days of work zone to accomplish project. Work for 5 hours for daytime work zone; 7 hours for night time; 8 hours for round the clock. Used in sub Usercost. |
| Numspans | Number of spans |
| partone | Interim variable used in sub AAA in calculated speed in queue. |
| parttwo | Interim variable used in sub AAA in calculating speed in queue. |
| PCC | Decimal fraction of autos in traffic stream. Used in sub BBB. |
| PW | Discounted value of bridge activities. Final total is BAC, the bridge activity cost. |
| PWcurrentact | Discounted cost of current activity. Used in calculating cumulative Bridge Activity Cost (BAC) |
| PWD(i) | Present Worth (PW) of Delay for Year i |
| Pwandcost | Range containing unit costs for all activities. Used to calculate total cost of each activity for the bridge of interest. |
| PWtotvalue | Present Worth (PW) of total value of delay from hour num |
| pwuserdelay | Discounted value of user delay for activity. Calculated in sub Usercost. |
| Queue | Number of vehicles slowed due to limited capacity in work zone |
| Queuedelay | Delay to pass through the queue at reduced speed. Calculated in sub AAA. |
| Queueel | Queue length. 50' per vehicle in queue assumed. Calculated in sub AAA. |
| Region | MDOT Region = {Bay, Grand1, Grand2, Metro1, Metro2, North, Southwest, Superior, University} |
| Route | Route on which bridge of interest is located. Included on Output page. |
| Route | Route on which bridge of interest is located. Included on Output page. |
| SL | Normal speed limit on the bridge (MPH); from traff db. |
| Speedqu | Speed (reduced) of vehicles in queue. Calculated in sub AAA. |
| tgr | Traffic growth rate as a percentage, e.g., 1.5%. Set based on trafgr and limits in sub Usercost. |
| thisactivitycost | Cost of single activity. Used only in calculating all activity costs in sub costs. |
| totalactivitycosts | Unit cost of activity times the number of lanes and number of spans. Calculated in sub costs. |
| Totdel | Total delay includes both wzdelay and queuedelay |
| Totdelhr | Total delay in hours |
| Totval | Value (\$) of Autodelay +Truckdelay |
| totvalhr | Value of total delay for each hour for autos and trucks. Used in sub BBB and sub Usercost. |
| Traff db | Worksheet including bridge identification, roadway, facility type, deck area, initial traffic, percent commercial vehicles, etc. |
| traffdist | Traffic distribution function for Michigan. Includes decimal fraction of traffic during each hour of 24-hour day. |
| trafgr | Annual traffic growth rate. Discounts similarly to discount rate. From traff db but limited to 3% or less. Negative values set to zero. Tgr is result. |

| | |
|--|---|
| Truckdelaycost | Monetary value (\$s) of truck portion of total delay |
| Unitcosts | Unit costs for activities. Per lane per span. From NCHRP study. |
| Urban | From traff db. Whether the bridge of interest is urban or not. |
| VLOOKUP(value, table, column, [range]) | Excel column lookup function |
| Wggrowth | Decimal fraction of Wage Growth Rate (set to constant of 0.5%) |
| WWT | Weighted Wage for Trucks (\$ / Hour) (\$21.19 then adjusted for average wage growth in Michigan of 0.5%) |
| wzdelay | Delay to vehicles traversing the work zone for all hours in workday or work night. |
| Wzdelayhr | Delay in hour num for reduced speed passing through workzone. |
| wzlength | Length of work zone in miles. |
| wzspeed | Work zone speed based on posted speed. For 65 mph or higher, wzspeed is 55 mph. Midrange speed, wzspeed is 10 miles per hour lower. For low speed routes, wzspeed is 5 miles per hour lower. Set in sub Usercost. |
| Year | Year in which a bridge activity occurs. Used in sub preswth to calculated discounted activity cost. |

Variables for Tool2: EAC-BAC and EAC-UDC for Preservation and No Preservation Activity Lists

| Variable | Description |
|---------------|---|
| Aadtzero | Average annual daily traffic at time 0; from traff db |
| AADT(i) | Average annual daily traffic in Year i (calculated using traffic growth rate.) |
| actcost | Total cost of a bridge activity. Used in calculating discounted activity cost in sub BAC. |
| actcostdb | Table of all total costs for all activities. Used in sub BAC. |
| Activitylists | Range containing all activity lists for all regions |
| Actlist | Activity list for the bridge of interest. |
| adjyear | Range of all years (1-80 with up to 3 activities per year) |
| adjyearcur | Set to zero for years less than bridge age; set to yearcur-age for others. |
| ADWV | Auto Delay Weighted Value / Vehicle / Hour (\$22.92 then adjusted for average wage growth rate in Michigan of 0.5%) |
| Autodelaycost | Monetary value (\$s) of auto portion of total delay |
| Boiregion | Region in which the bridge of interest is located. |
| Bridgeage | User inputs bridge age at start of analysis. |
| Bridgeid | Bridge identification number input by user, from traff db or region list |
| Cap | Traffic capacity in vehicles / hour / lane; function of speed. Calculated in sub capacity. |
| Carryover | Number of vehicles remaining in queue at beginning of next hour. |
| Comvehpercent | Percent Commercial Vehicles = (% Single Body Trucks + % Tractor Trailers); from traff db |
| County | County in which bridge of interest is located. Included on Output page. |

| | |
|-------------------------|--|
| cv | Percent commercial vehicles. From traff db. |
| cumnopresudc | Summation of UDC for all activities in no preservation activity list. |
| cumpresudc | Summation of UDC for all activities in preservation activity list. |
| Deckarea | Deck area in square feet (from Traff db) |
| Defage | Default bridge age=0 (new bridge). |
| Dr | Discount Rate (Decimal Fraction). Range is .005 to 0.5. Input in sub Disctrate. |
| Duract(i,a) | Duration of bridge Activity “a” in Year “iv” (Days) |
| EACnopres | Equivalent annual cost for no preservation activity list; calculated for both the activity costs and the user delay costs. |
| EACpres | Equivalent annual cost for capital maintenance/preservation activity list; calculated for both the activity costs and the user delay costs. |
| Hightype | Highway type in text field of traff db. Number of lanes is extracted from this text and converted to numeric. |
| hrlydf | Decimal fraction of traffic in each hour |
| hrlytraf(num) | Traffic volume in Hour “num”. Equals aadt*traffdist for current hour. |
| i, ii, iii, iv, etc. | Counters used in loops. |
| nopresact | Current activity for the no preservation list. |
| noprestotdelcost | UDC for single activity in no preservation activity list. |
| numlanes | Number of lanes on bridge; extracted from hightype |
| num | Hour of day when work is being performed (Ranges 1 to 24) Day work: $(09 \leq \text{num} \leq 16)$ Night work: $(01 \leq \text{num} \leq 06 \text{ OR } 20 \leq \text{num} \leq 24)$ |
| Numdays | Number of days of work zone to accomplish project. Work for 5 hours for daytime work zone; 7 hours for night time; 8 hours for round the clock. Used in sub Usercost. |
| Numspans | Number of spans |
| partone | Interim variable used in sub AAA in calculated speed in queue. |
| parttwo | Interim variable used in sub AAA in calculating speed in queue. |
| PCC | Decimal fraction of autos in traffic stream. Used in sub BBB. |
| pnpackduration | Subroutine looks up duration based on AADT for each activity in lists. |
| presact | Current activity being evaluation in sub BAC |
| Pres no pres activities | Worksheet included activities and times for preservation and no preservation lists. Costs and durations added during execution. |
| prestotdelcost | User delay costs for preservation activity |
| PW | Discounted value of bridge activities. Final total is BAC, the bridge activity cost. |
| PW2 | Discounted value of no preservation activities in sub BAC. |
| PWcurrentact | Discounted cost of current activity. Used in calculating cumulative Bridge Activity Cost (BAC) in sub BAC. |
| Pwandcost | Range containing unit costs for all activities. Used to calculate total cost of each activity for the bridge of interest. |
| PWtotvalue | Present Worth (PW) of total value of delay from hour num |
| pwuserdelay | Discounted value of user delay for activity. Calculated in sub pnpusercost. |
| Queue | Number of vehicles slowed due to limited capacity in work zone |
| Queuedelay | Delay to pass through the queue at reduced speed. Calculated in sub AAA. |

| | |
|---------------------|--|
| Queue _l | Queue length. 50' per vehicle in queue assumed. Calculated in sub AAA. |
| Region | MDOT Region = {Bay, Grand1, Grand2, Metro1, Metro2, North, Southwest, Superior, University} |
| Route | Route on which bridge of interest is located. Included on Output page. |
| SL | Normal speed limit on the bridge (MPH); from traff db. |
| Speed _{qu} | Speed (reduced) of vehicles in queue. Calculated in sub AAA. |
| tgr | Traffic growth rate set in sub pnpusercost. Limited to 3%. |
| Thisactivitycost | From pnp costs and durations worksheet. Unit cost of current activity. |
| totactcosts | Unit cost of activity times the number of lanes and number of spans. |
| totalactivitycost | Product of unit cost and number of spans and number of lanes |
| totdel | Total delay includes both wzdelay and queuedelay |
| totdelhr | Total delay in hours |
| totval | Value (\$) of Autodelay +Truckdelay |
| totvalhr | Value of total delay for each hour for autos and trucks. Used in sub BBB and sub pnpusercost. |
| Traff db | Worksheet including bridge identification, roadway, facility type, deck area, initial traffic, percent commercial vehicles, etc. |
| Traffdist | Hourly decimal fraction of traffic during each hour. |
| Traffgr | Traffic growth rate set in sub pnpusercost. Limited to 3%. |
| Unitcosts | Unit costs for activities. Per lane per span. From NCHRP study. |
| urban | From traff db. Whether the bridge of interest is urban or not. |
| Width | Estimated bridge width: 4 yards per lane + 8. |
| wzdelay | Summation of wzdelay over all hours of work |
| wzdelayhr | Workzone delay during one hour of work |
| wzlength | Length of work zone in miles. |
| wzspeed | Work zone speed based on posted speed. For 65 mph or higher, wzspeed is 55 mph. Midrange speed, wzspeed is 10 miles per hour lower. For low speed routes, wzspeed is 5 miles per hour lower. |
| year | Year being considered. Range is 0 to 80 for tool 2. |
| yearcur | Current year. Intermediate value. |

Chapter 11 Appendix B: Logic and Operations

Tool 1: BAC and UDC for Single Bridge over 75-year Analysis Period

1. User initiates analysis by clicking button on Output worksheet. An input box has user enter StrcNum from Traff db or from the region worksheet. User should consult the traffdb for the bridgeid prior to clicking the start analysis button.
2. Macro “definevariables” uses VLOOKUP function in Excel to get region, county, route, speed limit, urban vs not urban, deck area, highway type, initial average daily traffic, percent commercial vehicles, etc.
3. The highway type is a text string. The number of lanes is extracted from this string and becomes a numeric value. This extraction occurs in sub Lanes2.
4. Capacity per lane is calculated based on speed limit in Sub capacity. Three levels of capacity: 2100 vehicles per hour for speed limit of 65 or higher; speed limits of 45 to 64 have a capacity of 1600 vehicles per hour; speed limits less than 45 have a capacity of 1300 vehicles per hour.
5. The activity list associated with the region is selected in sub Activities.
6. Total cost of each activity in the region’s activity list is calculated in sub costs. It is based on unit costs from NCHRP national study, and then multiplied by the number of lanes and number of spans to get the total costs.
7. The user enters a discount rate in an input box from sub Disctrate. This must be between 0.005 and 0.05 or an error message is generated.
8. The present worth (discounted value) of each activity in the activity list is calculated and the cumulative total is the BAC or bridge activity cost. The result is written to the worksheet “output.”
9. Calculation of user delay costs consists of two components of delay: delay due to slowing of traffic in the workzone, and delay due to a queue. User costs are evaluated in sub Usercost, with calculation calls to Sub AAA and Sub BBB.
 - The duration of each activity in the region activity list is looked up in sub Activityduration. The durations are based on the national survey.
 - Based on the duration and whether the bridge is in an urban environment, work was scheduled to be either day work with work zone removal at end of day, night work (for urban locations with relatively short total durations), or workzones left in place over the extended period of the work.
 - Day time work with workzone removal at the end of the day begins at 9 am and ends at 4 pm, with one hour on each end for set up and removal of traffic control. Five hours of actual work. The duration in days is increased to account for the short work period.
 - Night work begins at 7 pm and ends at 6 am with one hour on each end for set up and removal of traffic control. 9 hours of actual work.
 - With work zone remaining in place, 8 hours of actual work, but user delay costs are incurred around the clock.
 - A test is made for a one-lane bridge. These are ramp bridges. Traffic is diverted to another ramp, resulting in a longer work zone but no queue.

- Traffic levels are increased using $aadt(i) = aadtzero(1 + tgr)^{year}$. TGR is capped at 3% to avoid excessively high traffic (which would require bridge capacity improvements).
- The traffic during each hour of activity is calculated as the product of the hourly traffic distribution function for that hour and the $aadt(i)$. This is compared to capacity to determine if a queue forms.
- The delay per vehicle due to the slowing in the workzone is the difference in the travel time at normal speed and the travel time at workzone speed.
- If the number of vehicles in the hour exceeds the capacity, then a queue forms and the queuespeed determines the delay due to the queue. If the queue extends beyond the hour, then the excess is carryover at the beginning of the next hour.
- The portion of the traffic that is automobile traffic is valued at 50% of the wage (wages increase by 0.5% per year, the recommended value for Michigan). Vehicle occupancy is also included in calculating the value of delay for each automobile.
- Commercial vehicles are valued at 100%, using the weighted hourly wage (also increased by 0.5% per year) for single body trucks and tractor trailers. Vehicle occupancy is included in the value of each hour for commercial vehicles.
- The user delay costs are discounted using the same discount rate as was used for bridge activity costs.
- The user delay costs are summed in sub Usercostsummation and the result is UDC, which is entered on the worksheet "output."

Tool 2: Preservation versus No Preservation for Bridge of User Specified Age

1. User initiates analysis by clicking button on "Output pres-no pres" worksheet. An input box has user enter STRCNum from Traff db or from the region worksheet. User should consult the traffdb for the bridgeid prior to clicking the start analysis button.
2. User inputs the bridge age when prompted by the input box.
3. Macro "presnopresbegin" uses VLOOKUP function in Excel to get region, county, route, speed limit, urban vs not urban, deck area, highway type, initial average daily traffic, percent commercial vehicles, etc. It also sequentially calls other subroutines to complete the calculations.
4. The highway type is a text string. The number of lanes is extracted from this string and becomes a numeric value. This extraction occurs in sub Lanes2.
5. Capacity per lane is calculated based on speed limit in Sub capacity. Three levels of capacity: 2100 vehicles per hour for speed limit of 65 or higher; speed limits of 45 to 64 have a capacity of 1600 vehicles per hour; speed limits less than 45 have a capacity of 1300 vehicles per hour.
6. Two activity lists are used in this tool. The preservation activity list extends to reconstruction in year 105, while the no preservation list has reconstruction at year 80. Because the time to reconstruction is different for the two cases, equivalent annual cost is calculated and used to determine the most advantageous activity list. The tool considers the preservation list first; then the no preservation case. Exactly the same procedure is used for both; only the activities for each list are different.

7. Total cost of each activity in both activity lists is calculated in sub pnp costs. It is based on unit costs from NCHRP national study, and then multiplied by the number of lanes and number of spans to get the total costs.
8. The user enters a discount rate in an input box from sub Discrate. This must be between 0.005 and 0.05 or an error message is generated.
9. The discounted present worth of the activity list is calculated (BAC) in sub BAC. The subroutine also includes the calculation of the Equivalent Annual Cost of the BAC, which is written to the output page.
10. Activity duration for each activity is determined in sub pnpactduration.
11. The user delay cost for each series of activities is calculated in sub pnpusercost. The logic is identical to that in Tool 1.
12. The total accumulated user delay cost for the series of activities is calculated in sub pnpusercostsummation. This subroutine also calculates the Equivalent annual cost of the user delay cost, which is written to the output page for both the preservation and the no preservation case.

Chapter 12 Appendix C: VBA Code

Sub capacity(sl, numlanes, cap)

'Determines capacity per lane based on speed limit(SL)

 If (sl >= 65) Then _

 cap = 2100 Else If (sl > 44) Then cap = 1600 Else cap = 1300

End Sub

Sub AAA(iv, numlanes, cap, sl, queue, queue1, queuedelay, carryover, wzspeed)

'Calculates speed in queue (speedqu), queue length (queue1) and queue delay (queuedelay) based on speed limit (SL), number of lanes (numlanes),_

'capacity (cap),work zone speed (wzspeed), and # of vehicles in queue (queue)

Dim speedqu As Double

Dim partone As Double, parttwo As Double

 partone = ((numlanes - 1) * cap) / (numlanes * cap)

 parttwo = (1 - partone) ^ 0.5

 speedqu = (sl / 2) * (1 - parttwo)

'estimate queue length as 50 feet per vehicle in queue; queue1 is in ft.

 queue1 = queue * 50

 queuedelay = (queue1 / 5280) * ((1 / speedqu) - (1 / wzspeed))

'carryover is number of vehicles remaining in queue at end of hour

 'carryover = queue + carryover

End Sub

Sub BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb, totdelhr)

'calculates the value of delay for cars and commercial vehicles. takes into account cars on personal _

'travel and work and uses weighted value of delay time. Truck value is also weighted between single _body trucks and tractor trailers.

'Value of time for both classes are inflated over time using the decimal fraction rate of wage growth.

'pcc is the decimal fraction of car travel; CV is the % commercial vehicles; _

ADWV is the weighted value of car delay including vehicle occupancy

'totdel is the total delay including wzdelay and queuedelay and the number of days for the activity

'Autodelay is the dollar value of car delay

'wwt is the hourly value of truck delay including wage growth

'truckdelay is the dollar value of commercial vehicle delay

'totval is the summation of autodelay and truckdelay

'pwtotvalue is the present worth of the total value of delay, using discount rate (DR) and year i

Dim pcc, cv, adwv, autodelay, wwt, truckdelay As Long

With ActiveWorkbook.Worksheets("traffic db")

Set traffddb = .Range(.Cells(2, 1), .Cells(2214, 20))

End With

cv = WorksheetFunction.VLookup(bridgeid, traffddb, 16, False)

pcc = (1 - cv) 'decimal fraction car traffic

'wggrowth in michigan overall is 0.5%. This is average wage growth rate

adwv = (22.92 * ((1 + 0.005) ^ year)) 'weighted value hourly wage per person per car per hour of delay

totdelhr = (wzdelay + queuedelay) * numdays 'totdelhr is total delay in hours

autodelaycost = totdelhr * pcc * adwv

wwt = (21.19 * ((1 + 0.005) ^ year)) 'weighted value hourly per person per commercial vehicle

```
truckdelaycost = totdelhr * wwt * cv
totvalhr = autodelaycost + truckdelaycost
End Sub
```

```
Sub definevariables()
Dim boiregion As String
Dim county As String
Dim hightype As String
Dim urban As String
Dim sl As Long
Dim bridgeid As Long
Dim traffdb As Range
Dim aadtzero As Double
Dim trafgr As Double, dr As Double
Dim comvehpercent As Double
Dim cvgrowthrate As Double
Dim numlanes As Long
Dim cap As Double
Dim actcostdur As Variant
Dim deckarea As Double
Dim unitcosts As Range
Dim totactcosts As Double
Dim traffdist As Variant
Dim activitylists As Range
Dim pwandcost As Range
Dim boiactlist As Range
```

Dim usercostvalues As Range

Dim actlist As Variant

'subroutine looks up values from the traffic data base for use in other subroutines

'subroutine calls other macros needed to find BAC and UDC

Pickbridge:

On Error GoTo BadEntry

' have user input the bridgeid

bridgeid = InputBox("StrcNum?", "unique bridge identifier #")

Worksheets("output").Range("B4").Value = bridgeid

Worksheets("output").Range("e4").Value = Date

With ActiveWorkbook.Worksheets("traffic db")

Set trafffdb = .Range(.Cells(2, 1), .Cells(2214, 20))

End With

'boi is bridge of interest

'traffdist contains hourly decimal fraction of traffic using Michigan averages

With ActiveWorkbook.Worksheets("hrly traf dist")

Set traffdist = .Range(.Cells(2, 1), .Cells(25, 2))

End With

'Lookup bridge attributes like region, county, route, urban, and speed limit and record them in output page

boiregion = Application.WorksheetFunction.VLookup(bridgeid, trafffdb, 5, False)

boiregion = Trim(boiregion)

Worksheets("output").Range("b6").Value = boiregion

```
county = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 6, False)
```

```
county = Trim(county)
```

```
Worksheets("output").Range("b7").Value = county
```

```
Route = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 4, False)
```

```
Route = Trim(Route)
```

```
Worksheets("output").Range("b8").Value = Route
```

```
urban = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 7, False)
```

```
sl = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 8, False)
```

```
Worksheets("output").Range("b9").Value = sl
```

```
hightype = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 10, False)
```

```
hightype = Trim(hightype)
```

```
'lookup traffic including aadt at time zero, percent commercial vehicles, traffic growth rates.
```

```
aadtzero = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 12, False)
```

```
Worksheets("output").Range("e7").Value = aadtzero
```

```
trafgr = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 13, False)
```

```
comvehpercent = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 16, False)
```

```
cvgrowthrate = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 17, False)
```

```
deckarea = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 20, False)
```

```
Worksheets("output").Range("e6").Value = deckarea
```

```
'sub calls lanes2 to extract the number of lanes from the string hightype.
```

```
Call Lanes2(hightype, numlanes)
```

```
'sub calls capacity to determine capacity per lane based on speed limit and number of lanes.
```

Call capacity(sl, numlanes, cap)

'sub calls activities to determine series of activities and their costs based on region

Call activities(boiregion, actlist)

'sub calculates total cost of activities in actcostdur based on number of lanes and deckarea

Call costs(numlanes, deckarea, unitcosts, totactcosts, numspans)

'sub has user input a discount rate and checks for value

Call Disctrate(dr)

'sub calculates present worth of the activity costs

Call Preswth(dr)

'sub looks up activity duration

Call Activityduration(aadtzero)

'sub calculates user costs, with calls to sub AAA and sub BBB

Call Usercost(iv, bridgeid, traffdb, traffdist, aadtzero, cap, numlanes, numspans, numdays, wzspeed, totdelhr, totdel, totvalhr, totval, pwuserdelay, dr)

'sub calculates cumulative UDC

Call Usercostsummation

Exit Sub

'The most common problem is entry of a number with no bridge associated with it

BadEntry:

msg = "An error occurred." & vbNewLine & nbnewline

msg = msg & "Make sure a valid bridge number is entered,"

msg = msg & vbNewLine & vbNewLine & "Try again?"

ans = MsgBox(msg, vbYesNo + vbCritical)

If ans = vbYes Then Resume Pickbridge

End Sub

Sub Lanes2(hightype, numlanes)

'examines string hightype for word stating number of lanes. Gets numeric number of lanes from text string.

```
If InStr(9, hightype, "One Lane") > 0 Then numlanes _  
= 1 Else If InStr(9, hightype, "Two Lane") > 0 Then numlanes _  
    = 2 Else If InStr(9, hightype, "Three") > 0 Then numlanes _  
        = 3 Else If InStr(9, hightype, "Four") > 0 Then numlanes _  
            = 4 Else If InStr(9, hightype, "Five") > 0 Then numlanes _  
                = 5 Else If InStr(9, hightype, "Six") > 0 Then numlanes _  
                    = 6 Else numlanes = -1
```

'places number of lanes in output sheet.

```
Worksheets("output").Range("e8").Value = numlanes
```

```
End Sub
```

```
Sub activities(boiregion, boiactlist)
```

'sub copies activity list to boiactlist based on region

```
Dim activitylists As Range
```

```
With ActiveWorkbook.Worksheets("activities")
```

```
    Set activitylists = .Range(.Cells(3, 1), .Cells(377, 10))
```

```
    Set boiactlist = .Range(.Cells(3, 11), .Cells(377, 11))
```

```
End With
```

```
If (StrComp(boiregion, "bay", vbTextCompare) = 0) Then boiactlist =  
activitylists.Range("b3:b377") _
```

```
    Else If ((StrComp(boiregion, "grand", vbTextCompare) = 0) And numlanes >= 4) Then boiactlist  
= activitylists.Range("d3:d377") _
```



```

    Else If ((StrComp(boiregion, "grand", vbTextCompare) = 0 And numlanes < 4)) Then
boiactlist = activitylists.Range("c3:c377") _

    Else If ((StrComp(boiregion, "metro", vbTextCompare) = 0 And numlanes <= 4)) Then
boiactlist = activitylists.Range("e3:e377") _

    Else If ((StrComp(boiregion, "metro", vbTextCompare) = 0 And numlanes > 4)) Then
boiactlist = activitylists.Range("f3:f377") _

    Else If (StrComp(boiregion, "north", vbTextCompare) = 0) Then boiactlist =
activitylists.Range("g3:g377") _

    Else If (StrComp(boiregion, "southwest", vbTextCompare) = 0) Then boiactlist =
activitylists.Range("h3:h377") _

    Else If (StrComp(boiregion, "superior", vbTextCompare) = 0) Then boiactlist =
activitylists.Range("i3:i377") _

    Else If (StrComp(boiregion, "university", vbTextCompare) = 0) Then boiactlist
= activitylists.Range("j3:j377") _

    Else boiactlist = "n/a"

```

```

ActiveWorkbook.Worksheets("activities").Range("k3:k377") = boiactlist
End Sub

```

```

Sub costs(numlanes, deckarea, unitcosts, totactcosts, numspans)
'sub calculates total cost of activities based on deck area and number of lanes on bridge
'estimated spanlength is 100 ft.

```

```

Dim i As Long
Dim width As Double
Dim ws As Worksheet
'note that deck area is in square feet.
Dim thisactivitycost As Double
Dim totalactivitycost As Double

```

```
width = (numlanes * 12) + 12
```

```
numspans = (deckarea / width) / 100
```

```
If (numspans < 1) Then
```

```
    numspans = 1
```

```
End If
```

```
With ActiveWorkbook.Worksheets("Durations and Costs")
```

```
    Set unitcosts = .Range(.Cells(4, 2), .Cells(38, 3))
```

```
End With
```

```
For i = 4 To 38
```

```
    thisactivitycost = ActiveWorkbook.Worksheets("Durations and Costs").Range("B" & i).Value2
```

```
    totalactivitycost = thisactivitycost * numlanes * numspans
```

```
    ActiveWorkbook.Worksheets("Durations and Costs").Range("C" & i).Value2 = totalactivitycost
```

```
Next i
```

```
End Sub
```

```
Sub Disctrate(dr)
```

```
    Range("I60").Select
```

```
    'creates an input box for discount rate that works with number input
```

```
    Dim drstring As Variant
```

```
    dr = Application.InputBox("range of discount rate should be 0.005 to 0.05; discount rate ? ")
```

```
    'check if user clicked cancel button and if so, give message
```

```
    drstring = TypeName(dr)
```

```
    'places entered discount rate on output sheet
```

```

Worksheets("output").Range("b11").Value = dr
'MsgBox "type name of dr is " & drstring
If (TypeName(dr) = "Boolean") And (dr = "False") Then

    MsgBox "You clicked the cancel button."

'check if user entered no input, and if so, give message
    Elself Len(dr) = 0 Then
        MsgBox "You didn't enter a discount rate."
        'user entered a value for discount rate which will be displayed
    Else
        MsgBox "Discount rate entered was " & dr
End If
End Sub

```

```

Sub Preswth(dr)
'Calculates the present worth of each activity in BOI activity list
'Summation of over all activities in 75-year period is BAC, the bridge activity cost
Dim PW As Double, year As Double, actcost As Double, PWcurrentact As Double
Dim ii As Integer
Dim boiact As String
Dim pwandcost As Range
Dim actcostdb As Range

Application.Goto ActiveWorkbook.Worksheets("activities").Range("a2:q377")
With ActiveWorkbook.Worksheets("Durations and Costs")
    Set actcostdb = .Range(.Cells(4, 1), .Cells(38, 7))

```

End With

With ActiveWorkbook.Worksheets("Activities")

.Range(.Cells(3, 13), .Cells(377, 13)).Clear

Set pwandcost = .Range(.Cells(3, 13), .Cells(377, 13))

End With

PW = 0

For ii = 3 To 377

boiact = ActiveWorkbook.Worksheets("Activities").Range("k" & ii).Value2

If Not Len(boiact) = 0 Then

'there is an activity in slot, so lookup cost

actcost = Application.WorksheetFunction.VLookup(boiact, actcostdb, 3, False)

ActiveWorkbook.Worksheets("activities").Range("L" & ii).Value2 = actcost

year = ActiveWorkbook.Worksheets("Activities").Range("A" & ii).Value2

'stored PW is cumulative present worth

PWcurrentact = (actcost) / ((1 + dr) ^ year)

PW = (PW + PWcurrentact)

ActiveWorkbook.Worksheets("Activities").Range("M" & ii).Value2 = PW

End If

Next ii

'write cumulative pw (BAC) to output page

Worksheets("output").Range("d14").Value = PW

End Sub

```

Sub Activityduration(aadtzero)
'Sub looks up duration based on AADT for each activity in series
Dim iii As Integer
Dim boiact As String
Dim duract As Double

ActiveWorkbook.Worksheets("Activities").Range("n2:n377").ClearContents
With ActiveWorkbook.Worksheets("Durations and Costs")
    Set actcostdb = .Range(.Cells(4, 1), .Cells(38, 17))
End With

For iii = 3 To 377
    boiact = ActiveWorkbook.Worksheets("Activities").Range("k" & iii).Value2
    'test if boiact is filled. i.e. length is not zero
    If Not Len(boiact) = 0 Then
        'test is high AADT
        If aadtzero >= 10000 Then
            duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 7, False)
            ActiveWorkbook.Worksheets("Activities").Range("N" & iii).Value2 = duract
        Else
            'moderate AADT
            duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 6, False)
            ActiveWorkbook.Worksheets("Activities").Range("N" & iii).Value2 = duract
        End If
    End If
Next iii
End Sub

```

```
Sub Usercost(iv, bridgeid, traffdb, traffdist, aadtzero, cap, numlanes, numspans, numdays,  
wzspeed, totdelhr, totdel, totvalhr, totval, pwuserdelay, dr)
```

```
'calculates user delays and costs
```

```
Dim num As Long, year As Variant
```

```
Dim wzlength As Double, hrlydf As Double, hrlytraff As Double, aadt As Double, tgr As Double
```

```
Dim carryover As Double, sl As Double
```

```
Dim urban As String
```

```
Dim trafgr As Double
```

```
With ActiveWorkbook.Worksheets("hrly traf dist")
```

```
    Set traffdist = .Range(.Cells(2, 1), .Cells(25, 2))
```

```
End With
```

```
'clear columns o,p,q in activities worksheet to hold total delay time, total value of delay time,  
and PW of delay time
```

```
With ActiveWorkbook.Worksheets("Activities")
```

```
    Set usercostvalues = .Range(.Cells(3, 15), .Cells(377, 17))
```

```
    .Range(.Cells(3, 15), .Cells(377, 17)).ClearContents
```

```
End With
```

```
With ActiveWorkbook.Worksheets("traffic db")
```

```
    Set traffdb = .Range(.Cells(2, 1), .Cells(2214, 20))
```

```
End With
```

```
'test for 1 lane bridge requiring ramp closure. If one lane, wz is 2 miles long. Otherwise 0.1  
mile on each side of bridge plus length of bridge.
```

```
If numlanes = 1 Then wzlength = 2 Else _
```

```
    wzlength = 0.2 + ((numspans * 100) / 5280)
```

'look up traffic growth rate, tgr

trafgr = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 13, False)

If trafgr > 0.03 _

Then tgr = 0.03 _

Else: If trafgr < 0 _

Then tgr = 0 _

Else: tgr = trafgr

Worksheets("output").Range("e9").Value = tgr

'lookup speed limit for bridge of interest

sl = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 8, False)

Select Case sl

Case 0 To 40

wzspeed = sl - 5

Case 41 To 64

wzspeed = sl - 10

Case Is >= 65

wzspeed = 55

End Select

'determine if bridge is in urban environment where nightwork is likely

urban = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 7, False)

'look at duration of activity (duract) and year (column A) to evaluate _

whether an activity occurred.

'all activity durations for 75 years with up to 5 activities per year

For iv = 3 To 377

year = ActiveWorkbook.Worksheets("activities").Range("a" & iv).Value2

duract = ActiveWorkbook.Worksheets("activities").Range("n" & iv).Value2

totval = 0

totdel = 0

pwtotvalue = 0

aadtzero = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 12, False)

aadt = aadtzero * ((1 + (tgr)) ^ year)

If Not Len(duract) = 0 Then

'there is an activity with duration, duract

Select Case duract

'*****Case with activity duration less than 5
days*****

Case 0.1 To 4.999

'an activity with duration less than 5 days: daytime work

pwuserdelay = 0

pwtotvalue = 0

queue = 0

wzdelay = 0

totdel = 0

totval = 0

carryover = 0

queuedelay = 0

numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr each wz
setup and removal

carryover = 0

'*****Test for case of one lane bridge. This case requires that the ramp be closed. No queue, but longer work zone and more traffic on detour.

If numlanes = 1 Then

For num = 9 To 17 'num is hour of day (i.e. 9 is 9 am to 10 am)

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt * 2 ' multiplier for doubling traffic on detourm ramp

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed) * hrlytraf))

wzdelay = wzdelay + wzdelayhr

'queue = 0

'carryover = 0

'queuedelay = 0

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf, totdelhr)

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel

ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 = pwuserdelay

'*****Duration less than 5 days, more than 2
lanes*****

Else: For num = 9 To 17

'traffdist has hourly decimal fraction of traffic each hour

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt

'calculate work zone delay without queue

'total workzone delay without queue for this hour is wzdelay (hrs)

wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

'determine if there is a queue

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

If queue <= 0 Then

queue = 0

carryover = 0

queuedelay = 0

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

Else: carryover = queue 'there is a queue so have queue delay

Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wszspeed)

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

End If

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

```

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 = pwuserdelay

End If

'*****Case for duration 5 to 15
days*****

Case 5 To 15 'duration is 5 to 15 days

'***** case for duration 5 to 15 days, urban
location*****

If urban = "urban" Then 'location is urban so nightwork required

    pwuserdelay = 0
    pwtotvalue = 0
    queue = 0
    queuedelay = 0
    wzdelay = 0

    numdays = duract * 8 / 7 'nightwork begins at 8pm and ends at 5 am with 1hr wz
setup before and after work

    carryover = 0

'***** Duration 5 to 15 days, one lane bridge. If one lane, detour is
required. No queue but _

    longer workzone and double traffic.

    'check for 1 lane bridge

If numlanes = 1 Then

    For num = 20 To 23

        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

        hrlytraf = hrlydf * aadt * 2

        wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

```

```

wzdelay = wzdelay + wzdelayhr
'queue = 0
'carryover = 0
'queuedelay = 0
Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

totdel = totdel + totdelhr

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
totval = totval + totvalhr
ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkboot.Worksheets("Activities").Range("q" & iv).Value2 = pwuserdelay

Next num
For num = 1 To 6
    hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
    hrlytraf = hrlydf * aadt * 2
    wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
    wzdelay = wzdelay + wzdelayhr
    'queue = 0
    'carryover = 0
    'queuedelay = 0
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

    totdel = totdel + totdelhr
    totval = totval + totvalhr

```

Next num

```
ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
```

```
ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
```

```
pwuserdelay = (totval) / ((1 + dr) ^ year)
```

```
ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =
```

pwuserdelay

```
'*****Duration 5 to 15 days, urban with 2 or more lanes  
*****
```

```
Else: pwuserdelay = 0
```

```
pwtotvalue = 0
```

```
queue = 0
```

```
queuedelay = 0
```

```
wzdelay = 0
```

```
carryover = 0
```

```
For num = 20 To 23 'more than 1 lane
```

```
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
hrlytraf = hrlydf * aadt
```

```
'total workzone delay without queue for this hour is wzdelayhr (hrs)
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
```

```
carryover = queue
```

```

        If queue <= 0 Then
            queue = 0
            carryover = 0
            queuedelay = 0
            Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        Else: carryover = queue
            Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)
            Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

        End If

```

```

totdel = totdel + totdelhr
totval = totval + totvalhr
wzdelay = wzdelay + wzdelayhr

```

Next num

```

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =
pwuserdelay

```

```

For num = 1 To 6 'hours from midnight to 6 am
    hrlydf = ActiveWorkbook.Worksheets("hrly traf
dist").Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
    hrlytraf = hrlydf * aadt

```

'total workzone delay without queue for this hour is wzdelayhr (hrs)

$wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspped))) * hrlytraf$

$wzdelay = wzdelay + wzdelayhr$

$queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))$

$carryover = queue$

If queue <= 0 Then

queue = 0

carryover = 0

queuedelay = 0

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

Else: carryover = queue

Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspped)

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

End If

$totdel = totdel + totdelhr$

$totval = totval + totvalhr$

Next num

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel

ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval

$pwuserdelay = (totval) / ((1 + dr) ^ year)$

```

ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =
pwuserdelay

End If

'***** Duration 5 to 15 days, not urban so work will be done during the
day*****

Else:

    pwuserdelay = 0
    pwtotvalue = 0
    queue = 0
    queuedelay = 0
    wzdelay = 0
    numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr
each wz setup and removal
    carryover = 0
    'num is hour of day (i.e. 9 is 9 am to 10 am)

    '***** Duration is 5 to 15 days, one lane
bridge*****

    If numlanes = 1 Then
        For num = 9 To 17
            hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
            hrlytraf = hrlydf * aadt * 2
            wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
            wzdelay = wzdelay + wzdelayhr
            'queue = 0
            'carryover = 0
            'queuedelay = 0
            Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

            totdel = totdel + totdelhr

```


totval = totval + totvalhr

Next num

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel

ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =

pwuserdelay

***** duration 5 to 15 days, 2+
lanes*****

Else:

pwuserdelay = 0

pwtotvalue = 0

queue = 0

queuedelay = 0

wzdelay = 0

carryover = 0

For num = 9 To 17

'traffdist has hourly decimal fraction of traffic each hour

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt

'calculate work zone delay without queue

'total workzone delay without queue for this hour is wzdelayhr (hrs)

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

'determine if there is a queue

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

```

        If queue <= 0 Then
            queue = 0
            carryover = 0
            queuedelay = 0
            Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

            'There is a queue
            Else: carryover = queue
                Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)
                Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)
            End If

            totdel = totdel + totdelhr
            totval = totval + totvalhr
            Next num
            ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
            ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
            pwuserdelay = (totval) / ((1 + dr) ^ year)
            ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =
pwuserdelay
        End If

    End If

    '*****Case for duration longer than 15
days*****
    Case Is > 15 'Duration is longer than 15 days and work zone will be left in place overnight
        carryover = 0

```

```

pwuserdelay = 0
pwtotvalue = 0
queue = 0
queuedelay = 0
wzdelay = 0
totval = 0
totdel = 0

'*****Duration >15 days, one lane
bridge*****

If numlanes = 1 Then
    For num = 0 To 23
        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
        hrlytraf = hrlydf * aadt * 2
        wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf
        wzdelay = wzdelay + wzdelayhr
        'queue = 0
        'carryover = 0
        'queuedelay = 0
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr
        totval = totval + totvalhr
    Next num

    ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel
    ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval
    pwuserdelay = (totval) / ((1 + dr) ^ year)

```

```

ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 =
pwuserdelay
'***** Duration >15 days, 2 or more
lanes*****
Else: For num = 0 To 23 'there are two or more lanes
'traffdist has hourly decimal fraction of traffic each hour
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
hrlytraf = hrlydf * aadt

'total workzone delay without queue for this hour is wzdelayhr (hrs)
wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf
wzdelay = wzdelay + wzdelayhr

'determine if there is a queue
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
If queue <= 0 Then
    queue = 0
    carryover = 0
    queuedelay = 0
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)
Else: carryover = queue
    Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wszspeed)
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)
End If
totdel = totdel + totdelhr
totval = totval + totvalhr

```

Next num

ActiveWorkbook.Worksheets("Activities").Range("o" & iv).Value2 = totdel

ActiveWorkbook.Worksheets("Activities").Range("p" & iv).Value2 = totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("Activities").Range("q" & iv).Value2 = pwuserdelay

End If

*****Error case for
duration*****

Case Else

MsgBox "duract did not meet case selection. Duract= " & duract

End Select

End If 'for test of duration of activity not equal zero

Next iv

End Sub

Sub Usercostsummation()

'adds the user delay costs for all activities over 75 year series. Result is UDC, user delay cost

Dim v As Long

Dim totdelcost As Double, cumuserdelaycost As Double

cumuserdelaycost = 0

For v = 3 To 377

totdelcost = ActiveWorkbook.Worksheets("Activities").Range("q" & v).Value2

cumuserdelaycost = cumuserdelaycost + totdelcost

Next v

```
ActiveWorkbook.Worksheets("Activities").Range("q378").Value2 = cumuserdelaycost  
Worksheets("output").Range("d16").Value = cumuserdelaycost  
End Sub
```

Code for Tool2: Preservation versus No Preservation

```
Sub presnopresbegin()  
Dim boiregion As String  
Dim county As String  
Dim hightype As String  
Dim urban As String  
Dim sl As Long  
Dim bridgeid As Long  
Dim traffdb As Range  
Dim aadtzero As Double  
Dim trafgr As Double, dr As Double  
Dim comvehpercent As Double  
Dim cvgrowthrate As Double  
Dim numlanes As Long  
Dim numdays As Double  
Dim duract As Double  
Dim cap As Double  
Dim deckarea As Double  
Dim unitcosts As Range  
Dim totactcosts As Double  
Dim traffdist As Variant  
Dim activitylists As Range  
Dim pwandcost As Range  
Dim boiactlist As Range
```

Dim usercostvalues As Range

Dim actlist As Variant

'subroutine looks up values from the traffic data base for use in other subroutines

'subroutine calls other macros needed to find BAC and UDC

Pickbridge:

On Error GoTo BadEntry

' have user input the bridgeid

bridgeid = InputBox("bridge id number?", "unique bridge identifier #")

MsgBox "bridge number = " & bridgeid

'default age is 0

With ActiveWorkbook.Worksheets("traffic db")

Set traffddb = .Range(.Cells(2, 1), .Cells(2214, 20))

End With

'defage is default age and is zero(a new bridge).

Defage = 0

bridgeage = InputBox("bridge age?", "Bridge Age", Defage)

If bridgeage = "" Then Exit Sub 'Canceled

If IsNumeric(bridgeage) Then

If bridgeage > 0 Then age = bridgeage

Else

MsgBox "invalid bridge age. Value must be >= 0"

End If

Worksheets("output pres-nopres").Range("B4").Value = bridgeid

Worksheets("output pres-nopres").Range("e4").Value = Date

Worksheets("output pres-nopres").Range("e9").Value = age

'boi is bridge of interest

'traffdist contains hourly decimal fraction of traffic using Michigan averages

With ActiveWorkbook.Worksheets("hrly traf dist")

Set traffdist = .Range(.Cells(2, 1), .Cells(25, 2))

End With

'Lookup bridge attributes like region, county, route, urban, and speed limit and record them in output page

boiregion = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 5, False)

boiregion = Trim(boiregion)

Worksheets("output pres-nopres").Range("b6").Value = boiregion

county = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 6, False)

county = Trim(county)

Worksheets("output pres-nopres").Range("b7").Value = county

Route = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 4, False)

Route = Trim(Route)

Worksheets("output pres-nopres").Range("b8").Value = Route

urban = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 7, False)

sl = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 8, False)

Worksheets("output pres-nopres").Range("b9").Value = sl

hightype = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 10, False)

hightype = Trim(hightype)

'lookup traffic including aadt at time zero, percent commercial vehicles, traffic growth rates.

aadtzero = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 12, False)


```
Worksheets("output pres-nopres").Range("e7").Value = aadtzero
```

```
trafgr = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 13, False)
```

```
comvehpercent = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 16, False)
```

```
cvgrowthrate = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 17, False)
```

```
deckarea = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 20, False)
```

```
Worksheets("output pres-nopres").Range("e6").Value = deckarea
```

```
'sub calls lanes2 to extract the number of lanes from the string hightype.
```

```
Call Lanes2(hightype, numlanes)
```

```
Worksheets("output pres-nopres").Range("e8").Value = numlanes
```

```
'sub calls capacity to determine capacity per lane based on speed limit.
```

```
Call capacity(sl, numlanes, cap)
```

```
'sub calls activity lists for preservation versus no preservation
```

```
Call pnpactivities(age)
```

```
'sub calculates total cost of activities based on number of lanes and deckarea
```

```
Call pnpcosts(numlanes, deckarea, unitcosts, totactcosts, numspans)
```

```
'sub has user input a discount rate and checks for value
```

```
Call Disctrate(dr)
```

```
'sub calculates present worth of the activity costs
```

```
Call BAC (dr, age)
```

```
'sub looks up activity duration
```

```
Call pnpactduration(aadtzero)
```

```

'sub calculates user costs, with calls to sub AAA and sub BBB

Call pnpusercost(bridgeid, trafffdb, traffdist, aadtzero, cap, numlanes, numspans, numdays,
wzspeed, totdelhr, totdel, totvalhr, totval, pwuserdelay, dr)

'sub calculates cumulative UDC

Call pnpusercostsummation(dr, age)

Exit Sub

```

'The most common problem is entry of a StrcNum with no bridge associated with it

BadEntry:

```

    msg = "An error occurred." & vbNewLine & nbnewline
    msg = msg & "Make sure a valid bridge number is entered,"
    msg = msg & vbNewLine & vbNewLine & "Try again?"
    ans = MsgBox(msg, vbYesNo + vbCritical)

    If ans = vbYes Then Resume Pickbridge

End Sub

```

Sub pnpactivities(age)

'this subroutine takes the age of the bridge and adjusts the time to be zero for years before age, and year-age for years after.

Dim adjyear As Range

Dim adjyearcur As Variant

Dim year As Range

Dim i As Integer

Dim yearcur As Integer

ActiveWorkbook.Worksheets("pres no pres activities").Activate

Range("a3:o242").Select

'for preservation case, activities extend to 105 years.

For i = 4 To 318

yearcur = ActiveWorkbook.Worksheets("pres no pres activities").Range("a" & i).Value2

If yearcur < age _

Then

adjyearcur = 0

Worksheets("pres no pres activities").Range("b" & i).Value = adjyearcur

ElseIf yearcur = age Then

adjyearcur = 0

Worksheets("pres no pres activities").Range("b" & i).Value2 = adjyearcur

Else 'year is greater than age

adjyearcur = yearcur - age

Worksheets("pres no pres activities").Range("b" & i).Value2 = adjyearcur

End If

'for no preservation case, activities extend to 105 years, by duplicating first 25 years after the 80 original. No need to recalculate adjyear.

Next i

End Sub

Sub pnpcosts(numlanes, deckarea, unitcosts, totactcosts, numspans)

'sub calculates total cost of activities based on deck area and number of lanes on bridge

'estimated spanlength is 100 ft.

Dim ii As Long

Dim width As Double

Dim ws As Worksheet

'note that deck area is in square feet

Dim thisactivitycost As Double

Dim totalactivitycost As Double

width = (numlanes * 12) + 12

numspans = (deckarea / width) / 100

If (numspans < 1) Then

numspans = 1

End If

ActiveWorkbook.Worksheets("pnp costs and durations").Activate

Range("a3:g10").Select

For ii = 3 To 10

thisactivitycost = ActiveWorkbook.Worksheets("pnp costs and durations").Range("B" & ii).Value2

totalactivitycost = thisactivitycost * numlanes * numspans

ActiveWorkbook.Worksheets("pnp costs and durations").Range("C" & ii).Value2 = totalactivitycost

Next ii

End Sub

Sub BAC (dr, age)

'Calculates the present worth of each activity in activity list for preservation vs no preservation analysis

'Summation of over all activities in 80-year period is BAC, the bridge activity cost

Dim PW As Double, year As Double, actcost As Double, PWcurrentact As Double

Dim ii As Integer

Dim presact As String

Dim pwandcost As Range

Dim actcostdb As Range

Dim adjyear As Double

Sheets("pres no pres activities").Activate

Range("d4:e242").ClearContents

Range("l4:m242").ClearContents

With ActiveWorkbook.Worksheets("pnp costs and durations")

Set actcostdb = .Range(.Cells(3, 1), .Cells(10, 7))

End With

PW = 0

'consider preservation activities

For ii = 4 To 318

adjyear = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & ii).Value2

If Not (adjyear = 0) Then

presact = ActiveWorkbook.Worksheets("pres no pres activities").Range("c" & ii).Value2

If Not Len(presact) = 0 Then

'there is an activity in slot, so lookup cost

actcost = Application.WorksheetFunction.VLookup(presact, actcostdb, 3, False)

ActiveWorkbook.Worksheets("pres no pres activities").Range("d" & ii).Value2 = actcost

'stored PW is cumulative present worth

```

    PWcurrentact = (actcost) / ((1 + dr) ^ adjyear)

    PW = (PW + PWcurrentact)

    ActiveWorkbook.Worksheets("pres no pres activities").Range("e" & ii).Value2 = PW

End If

End If

Next ii

'write cumulative pw (BAC) to output page
Worksheets("Output pres-nopres").Range("b15").Value = PW

'calculate the equivalent annual cost for the preservation case
n = 105 - age
EACpres = (PW * dr) / (1 - (1 + dr) ^ -n)
Worksheets("Output pres-nopres").Range("b11").Value = dr
Worksheets("Output pres-nopres").Range("b18").Value = EACpres

'MsgBox ("EAC of preservation series = " & EACpres)

'*****

PW2 = 0

'consider no preservation activities
For iii = 4 To 318

    adjyear = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & iii).Value2

    If Not (adjyear = 0) Then

        nopresact = ActiveWorkbook.Worksheets("pres no pres activities").Range("k" & iii).Value2

        If Not Len(nopresact) = 0 Then

            'there is an activity in slot, so lookup cost

            actcost = Application.WorksheetFunction.VLookup(nopresact, actcostdb, 3, False)

            ActiveWorkbook.Worksheets("pres no pres activities").Range("l" & iii).Value2 = actcost

```

```

        'stored PW is cumulative present worth
        PWcurrentact = (actcost) / ((1 + dr) ^ adjyear)
        PW2 = (PW2 + PWcurrentact)

        ActiveWorkbook.Worksheets("pres no pres activities").Range("m" & iii).Value2 = PW2
    End If
End If
Next iii

'write cumulative pw (BAC) to output page
'MsgBox ("BAC for no preservation case is " & PW2)
Worksheets("Output pres-nopres").Range("d15").Value = PW2


nn = 105 - age


'Calculate EAC for no preservation option
EACnopres = (PW2 * dr) / (1 - (1 + dr) ^ (-nn))
Worksheets("Output pres-nopres").Range("b11").Value = dr
Worksheets("Output pres-nopres").Range("d18").Value = EACnopres


End Sub


Sub pnpactduration(aadtzero)
'Sub looks up duration based on AADT for each activity in series
Dim iv As Integer
Dim v As Integer
Dim boiact As String
Dim duractlist As String

```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("f4:i244").ClearContents
ActiveWorkbook.Worksheets("pres no pres activities").Range("n4:q244").ClearContents
```

```
With ActiveWorkbook.Worksheets("pnp costs and durations")
```

```
    Set actcostdb = .Range(.Cells(3, 1), .Cells(10, 7))
```

```
End With
```

```
'look up durations for preservation case
```

```
For iv = 4 To 318
```

```
    adjyear = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & iv).Value2
```

```
    If Not (adjyear = 0) Then
```

```
        boiact = ActiveWorkbook.Worksheets("pres no pres activities").Range("c" & iv).Value2
```

```
        'test if boiact is filled. i.e. length is not zero
```

```
        If Not Len(boiact) = 0 Then
```

```
            'test is high AADT
```

```
            If aadtzero >= 10000 Then
```

```
                'high traffic duration
```

```
                duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 7, False)
```

```
                ActiveWorkbook.Worksheets("pres no pres activities").Range("f" & iv).Value2 = duract
```

```
            Else
```

```
                'moderate AADT
```

```
                duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 6, False)
```

```
                ActiveWorkbook.Worksheets("pres no pres activities").Range("f" & iv).Value2 = duract
```

```
            End If
```

```
        End If
```



```

End If
Next iv

'look up durations for no preservation case
For v = 4 To 318
    adjyear = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & v).Value2
    If Not (adjyear = 0) Then
        boiact = ActiveWorkbook.Worksheets("pres no pres activities").Range("k" & v).Value2
        'test if boiact is filled. i.e. length is not zero
        If Not Len(boiact) = 0 Then
            'test is high AADT
            If aadtzero >= 10000 Then
                'high traffic duration
                duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 7, False)
                ActiveWorkbook.Worksheets("pres no pres activities").Range("n" & v).Value2 = duract
            Else
                'moderate AADT
                duract = Application.WorksheetFunction.VLookup(boiact, actcostdb, 6, False)
                ActiveWorkbook.Worksheets("pres no pres activities").Range("n" & v).Value2 = duract
            End If
        End If
    End If
Next v
End Sub

```

```
Sub pnpusercost(bridgeid, traffdb, traffdist, aadtzero, cap, numlanes, numspans, numdays,  
wzspeed, totdelhr, totdel, totvalhr, totval, pwuserdelay, dr)
```

```
'calculates user delays and costs
```

```
Dim num As Long, year As Variant
```

```
Dim wzlength As Double, hrlydf As Double, hrlytraff As Double, aadt As Double, tgr As Double
```

```
Dim carryover As Double, sl As Double
```

```
Dim urban As String
```

```
Dim vi As Integer, vii As Integer, iv As Integer
```

```
With ActiveWorkbook.Worksheets("hrly traf dist")
```

```
    Set traffdist = .Range(.Cells(2, 1), .Cells(25, 2))
```

```
End With
```

```
'clear columns in pres no pres activities worksheet to hold total delay time, total value of delay  
time, and PW of delay time
```

```
With ActiveWorkbook.Worksheets("pres no pres activities")
```

```
    Set pusercostvalues = .Range(.Cells(4, 7), .Cells(244, 9))
```

```
    .Range(.Cells(4, 7), .Cells(244, 9)).ClearContents
```

```
    Set npusercostvalues = .Range(.Cells(4, 15), .Cells(244, 17))
```

```
    .Range(.Cells(4, 15), .Cells(244, 17)).ClearContents
```

```
End With
```

```
With ActiveWorkbook.Worksheets("traffic db")
```

```
    Set traffdb = .Range(.Cells(2, 1), .Cells(2214, 20))
```

```
End With
```

```
'test for 1 lane bridge requiring ramp closure. If one lane, wz is 2 miles long. Otherwise 0.1  
mile on each side of bridge plus length of bridge.
```

```

If numlanes = 1 Then wzlength = 2 Else _
    wzlength = 0.2 + ((numspans * 100) / 5280)

'look up traffic growth rate, tgr
trafgr = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 13, False)
If trafgr > 0.03 _
    Then tgr = 0.03 _
    Else: If trafgr < 0 _
        Then tgr = 0 _
        Else: tgr = trafgr
Worksheets("Output pres-nopres").Range("e10").Value = tgr

'lookup speed limit for bridge of interest
sl = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 8, False)
Select Case sl
    Case 0 To 40
        wzspeed = sl - 5
    Case 41 To 64
        wzspeed = sl - 10
    Case Is >= 65
        wzspeed = 55
End Select

'determine if bridge is in urban environment where nightwork is likely
urban = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 7, False)
'Preservation case

```

'look at duration of activity (duract)in column f and adjyear (column b) to evaluate _
whether an activity occurred.

For vi = 4 To 318

'using the adjusted year for year

year = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & vi).Value2

totdelhr = 0

If Not year = 0 Then

duract = ActiveWorkbook.Worksheets("pres no pres activities").Range("f" & vi).Value2

totval = 0

totdel = 0

pwtotvalue = 0

aadtzero = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 12, False)

aadt = aadtzero * ((1 + (tgr)) ^ year)

If Not Len(duract) = 0 Then

'there is an activity with duration, duract

Select Case duract

'***** pres case with duration less than 5
days*****

Case 0.1 To 4.999

'an activity with duration less than 5 days: daytime work

pwuserdelay = 0

pwtotvalue = 0

queue = 0

wzdelay = 0

totdel = 0

```

totval = 0

carryover = 0

queuedelay = 0

numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr each wz
setup and removal

carryover = 0

'num is hour of day (i.e. 9 is 9 am to 10 am)

```

'Test for case of one lane bridge. This case requires that the ramp be closed. No queue, but longer work zone and more traffic on detour.

```

'***** pres case with duration less than 5 days and 1 lane
bridge*****

```

```

If numlanes = 1 Then

    For num = 9 To 17

        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

        hrlytraf = hrlydf * aadt * 2 ' multiplier for doubling traffic on detourm ramp

        wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed) * hrlytraf))

        wzdelay = wzdelay + wzdelayhr

        'queue = 0

        'carryover = 0

        'queuedelay = 0

        iv = vi

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr

        totval = totval + totvalhr

    Next num

    ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =  
totval
```

```
pwuserdelay = (totval) / ((1 + dr) ^ year)
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =  
pwuserdelay
```

```
'numlanes>=2
```

```
Else:
```

```
For num = 9 To 17
```

```
'traffdist has hourly decimal fraction of traffic each hour
```

```
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
hrlytraf = hrlydf * aadt
```

```
'calculate work zone delay without queue
```

```
'total workzone delay without queue for this hour is wzdelay (hrs)
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
'determine if there is a queue
```

```
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
```

```
If queue <= 0 Then
```

```
queue = 0
```

```
carryover = 0
```

```
queuedelay = 0
```

```
iv = vi
```

```
Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,  
totdelhr)
```

```
Else: carryover = queue 'there is a queue so have queue delay
```

```
iv = vi
```

```

        Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wzspeed)
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

    End If

    totdel = totdel + totdelhr
    totval = totval + totvalhr

Next num

    ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel
    ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

    pwuserdelay = (totval) / ((1 + dr) ^ year)
    ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

    End If

    '***** pres case with duration 5 to 15
days*****
    Case 5 To 15 'duration is 5 to 15 days
        pwuserdelay = 0
        pwtotvalue = 0
        queue = 0
        carryover = 0
        queuedelay = 0
        wzdelay = 0

        '***** pres case with duration 5 to 15 days, urban requiring
nightwork *****

```

```

If urban = "urban" Then 'location is urban so nightwork required

    pwuserdelay = 0
    pwtotvalue = 0
    queue = 0

    numdays = duract * 8 / 7 'nightwork begins at 8pm and ends at 5 am with 1hr wz
    setup before and after work

    carryover = 0
    totval = 0
    totdel = 0

    'Test for one lane bridge (ramp condition). If one lane, detour is required. No queue
    but _

    longer workzone and double traffic.

    '*****pres case, urban, with duration 5 to 15 days and one
    lane*****

    If numlanes = 1 Then

        For num = 20 To 23

            hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
            hrlytraf = hrlydf * aadt * 2
            wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
            wzdelay = wzdelay + wzdelayhr

            'queue = 0
            'carryover = 0
            'queuedelay = 0

            iv = vi

            Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
            totdelhr)

            totdel = totdel + totdelhr

```



```

ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

totval = totval + totvalhr

ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkboot.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

```

Next num

For num = 1 To 6 'work from midnight to 6 am

```

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
hrlytraf = hrlydf * aadt * 2
wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf
wzdelay = wzdelay + wzdelayhr

iv = vi

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

totdel = totdel + totdelhr

totval = totval + totvalhr

```

Next num

```

ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

```

```
'***** pres case with duration 5-15 days, urban, 2 or more  
lanes*****
```

```
'bridge has 2 or more lanes
```

```
Else:
```

```
    pwuserdelay = 0
```

```
    pwtotvalue = 0
```

```
    queue = 0
```

```
    carryover = 0
```

```
    queuedelay = 0
```

```
    wzdelay = 0
```

```
For num = 20 To 23 'more than 1 lane
```

```
    hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
    hrlytraf = hrlydf * aadt
```

```
'total workzone delay without queue for this hour is wzdelayhr (hrs)
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
```

```
carryover = queue
```

```
If queue <= 0 Then
```

```
    queue = 0
```

```
    carryover = 0
```

```
    queuedelay = 0
```

```
    iv = vi
```

```
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,  
totdelhr)
```

```

Else: carryover = queue
    iv = vi
    Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)
End If

totdel = totdel + totdelhr
totval = totval + totvalhr
wzdelay = wzdelay + wzdelayhr

Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel
ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval
pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

For num = 1 To 6 'hours from midnight to 6 am
    hrlydf = ActiveWorkbook.Worksheets("hrly traf
dist").Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
    hrlytraf = hrlydf * aadt
    'total workzone delay without queue for this hour is wzdelayhr (hrs)
    wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
    wzdelay = wzdelay + wzdelayhr

```

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

carryover = queue

If queue <= 0 Then

queue = 0

carryover = 0

queuedelay = 0

iv = vi

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

Else: carryover = queue

iv = vi

Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

End If

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

End If

```
'*****pres case with duration 5 to 15 days, not urban
*****
```

'Else bridge is not in urban region so work will be done during the day

Else:

pwuserdelay = 0

pwtotvalue = 0

queue = 0

carryover = 0

queuedelay = 0

wzdelay = 0

numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr
each wz setup and removal

carryover = 0

'num is hour of day (i.e. 9 is 9 am to 10 am)

'test for one lane bridge

```
'*****pres case with duration 5 to 15 days, not urban, one lane bridge
*****
```

If numlanes = 1 Then

For num = 9 To 17

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt * 2

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

'queue = 0

'carryover = 0

'queuedelay = 0

```

        iv = vi
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr
        totval = totval + totvalhr
        Next num

        ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

        ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2
= totval

        pwuserdelay = (totval) / ((1 + dr) ^ year)
        ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

        '*****pres case with duration 5 to 15 days, not urban, 2 or more lanes
        *****

        'bridge has 2 or more lanes
        Else: For num = 9 To 17

            'traffdist has hourly decimal fraction of traffic each hour
            hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
            hrlytraf = hrlydf * aadt

            'calculate work zone delay without queue
            'total workzone delay without queue for this hour is wzdelayhr (hrs)
            wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
            wzdelay = wzdelay + wzdelayhr

            'determine if there is a queue
            queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

```

```

    If queue <= 0 Then
        queue = 0
        carryover = 0
        queuedelay = 0
        iv = vi
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

    'There is a queue
    Else: carryover = queue
        iv = vi
        Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

    End If

    totdel = totdel + totdelhr
    totval = totval + totvalhr
    Next num

    ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

    ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

    pwuserdelay = (totval) / ((1 + dr) ^ year)
    ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay
End If

```

End If

'*****pres case with duration greater than 15 days*****

Case Is > 15 'Duration is longer than 15 days and work zone will be left in place overnight

pwuserdelay = 0

pwtotvalue = 0

queue = 0

carryover = 0

queuedelay = 0

wzdelay = 0

numdays = duract

totval = 0

totdel = 0

'test for one lane bridge

If numlanes = 1 Then

For num = 0 To 23

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt * 2

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

'queue = 0

'carryover = 0

'queuedelay = 0

iv = vi

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf, totdelhr)

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

totdel ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =

totval ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =

pwuserdelay = (totval) / ((1 + dr) ^ year)

pwuserdelay ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =

lanes '*****pres case with duration>15 days and 2+

Else: For num = 0 To 23 'there are two or more lanes

'traffdist has hourly decimal fraction of traffic each hour

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt

'total workzone delay without queue for this hour is wzdelayhr (hrs)

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspped))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

'determine if there is a queue

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

If queue <= 0 Then

 queue = 0

 carryover = 0

 queuedelay = 0

 iv = vi

```

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

    Else: carryover = queue

        iv = vi

        Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wzspeed)

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

    End If

    totdel = totdel + totdelhr
    totval = totval + totvalhr
Next num

    ActiveWorkbook.Worksheets("pres no pres activities").Range("g" & vi).Value2 =
totdel

    ActiveWorkbook.Worksheets("pres no pres activities").Range("h" & vi).Value2 =
totval

    pwuserdelay = (totval) / ((1 + dr) ^ year)

    ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & vi).Value2 =
pwuserdelay

    End If

    Case Else

        'MsgBox "duract did not meet case selection. Duract= " & duract

    End Select

    End If 'for test of duration of activity not equal zero

    End If 'case for adjyear not equal zero

    Next vi

' End of Preservation case

```

*****Calculate delay costs for No preservation case*****

'look at duration of activity (duract)in column n and adjyear (column b) to evaluate _
whether an activity occurred.

For vii = 4 To 318

'using the adjusted year for year

year = ActiveWorkbook.Worksheets("pres no pres activities").Range("b" & vii).Value2

totdelhr = 0

If Not year = 0 Then

duract = ActiveWorkbook.Worksheets("pres no pres activities").Range("n" & vii).Value2

totval = 0

totdel = 0

pwtotvalue = 0

aadtzero = Application.WorksheetFunction.VLookup(bridgeid, traffdb, 12, False)

aadt = aadtzero * ((1 + (tgr)) ^ year)

If Not Len(duract) = 0 Then

'there is an activity with duration, duract

Select Case duract

*****No pres case with duration less than 5
days*****

Case 0.1 To 4.999

'an activity with duration less than 5 days: daytime work

pwuserdelay = 0

pwtotvalue = 0

queue = 0

```

wzdelay = 0

totdel = 0

totval = 0

numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr each wz
setup and removal

carryover = 0

'num is hour of day (i.e. 9 is 9 am to 10 am)

'Test for case of one lane bridge. This case requires that the ramp be closed. No
queue, but longer work zone and more traffic on detour.

'*****no pres, duration less than 5 days, one lane
bridge*****

If numlanes = 1 Then
    For num = 9 To 17
        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
        hrlytraf = hrlydf * aadt * 2 ' multiplier for doubling traffic on detour ramp
        wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspped) * hrlytraf))
        wzdelay = wzdelay + wzdelayhr
        'queue = 0
        'carryover = 0
        'queuedelay = 0

        iv = vii

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr
        totval = totval + totvalhr
    Next num

```

```

ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2 =
totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2 =
totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2 =
pwuserdelay

'*****no pres, duration less than 5 days, 2 or more
lanes*****

'numlanes>=2

Else: For num = 9 To 17

'traffdist has hourly decimal fraction of traffic each hour
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
hrlytraf = hrlydf * aadt

'calculate work zone delay without queue
'total workzone delay without queue for this hour is wzdelay (hrs)
wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf
wzdelay = wzdelay + wzdelayhr

'determine if there is a queue
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
If queue <= 0 Then
    queue = 0
    carryover = 0
    queuedelay = 0
    iv = vii

    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

```

```

Else: carryover = queue 'there is a queue so have queue delay
    iv = vii
    Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wzspeed)
    Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)
End If

totdel = totdel + totdelhr
totval = totval + totvalhr
Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2 =
totdel
ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2 =
totval
pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2 =
pwuserdelay

End If

'*****no pres case with duration 5 to 15
days*****
Case 5 To 15 'duration is 5 to 15 days
'*****no pres case with duration 5 to 15 days,
urban*****
If urban = "urban" Then 'location is urban so nightwork required
    pwuserdelay = 0
    pwtotvalue = 0
    queue = 0

```

```

carryover = 0
queuedelay = 0
wzdelay = 0

numdays = duract * 8 / 7 'nightwork begins at 8pm and ends at 5 am with 1hr wz
setup before and after work
carryover = 0

totdel = 0
totval = 0

'Test for one lane bridge (ramp condition). If one lane, detour is required. No queue
but _
longer workzone and double traffic.

If numlanes = 1 Then
    For num = 20 To 23
        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
        hrlytraf = hrlydf * aadt * 2
        wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
        wzdelay = wzdelay + wzdelayhr
        iv = vii
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr

        ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel

        totval = totval + totvalhr

        ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval

        pwuserdelay = (totval) / ((1 + dr) ^ year)

```

```
ActiveWorkboot.Worksheets("pres no pres activities").Range("q" & vii).Value2 =  
pwuserdelay
```

```
Next num
```

```
For num = 1 To 6
```

```
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
hrlytraf = hrlydf * aadt * 2
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
iv = vii
```

```
Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,  
totdelhr)
```

```
totdel = totdel + totdelhr
```

```
totval = totval + totvalhr
```

```
Next num
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2  
= totdel
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2  
= totval
```

```
pwuserdelay = (totval) / ((1 + dr) ^ year)
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2  
= pwuserdelay
```

```
***** no pres case with duration 5 to 15 days, 2+  
lanes*****
```

```
Else:
```

```
pwuserdelay = 0
```

```
pwtotvalue = 0
```

```
queue = 0
```


carryover = 0

queuedelay = 0

wzdelay = 0

For num = 20 To 23 'more than 1 lane

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt

'total workzone delay without queue for this hour is wzdelayhr (hrs)

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

carryover = queue

If queue <= 0 Then

queue = 0

carryover = 0

queuedelay = 0

iv = vii

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,

totdelhr)

Else: carryover = queue

iv = vii

Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,

wzspeed)

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,

totdelhr)

End If

totdel = totdel + totdelhr

totval = totval + totvalhr

wzdelay = wzdelay + wzdelayhr

Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2
= pwuserdelay

For num = 1 To 6 'hours from midnight to 6 am

hrlydf = ActiveWorkbook.Worksheets("hrly traf
dist").Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt

'total workzone delay without queue for this hour is wzdelayhr (hrs)

wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))

carryover = queue

If queue <= 0 Then

queue = 0

carryover = 0

queuedelay = 0

iv = vii

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

```

Else: carryover = queue

iv = vii

Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

End If

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval

pwuserdelay = (totval) / ((1 + dr) ^ year)

ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2
= pwuserdelay

End If

'*****no pres, duration 5-15 days, not
urban*****

'Else bridge is not in urban region so work will be done during the day

Else:

pwuserdelay = 0

pwtotvalue = 0

queue = 0

carryover = 0

queuedelay = 0

```

```

wzdelay = 0

numdays = duract * 8 / 5 'day work begins at 9 am and ends at 4 pm with 1 hr
each wz setup and removal

carryover = 0

'num is hour of day (i.e. 9 is 9 am to 10 am)

'test for one lane bridge

If numlanes = 1 Then

    For num = 9 To 17

        hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

        hrlytraf = hrlydf * aadt * 2

        wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

        wzdelay = wzdelay + wzdelayhr

        'queue = 0

        'carryover = 0

        'queuedelay = 0

        iv = vii

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

        totdel = totdel + totdelhr

        totval = totval + totvalhr

    Next num

    ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel

    ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval

    pwuserdelay = (totval) / ((1 + dr) ^ year)

    ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2
= pwuserdelay

```

```
'*****no pres case, duration 5-15 days, 2+
laness*****
```

```
'bridge has 2 or more lanes
```

```
Else:
```

```
    pwuserdelay = 0
```

```
    pwtotvalue = 0
```

```
    queue = 0
```

```
    carryover = 0
```

```
    queuedelay = 0
```

```
    wzdelay = 0
```

```
For num = 9 To 17
```

```
'traffdist has hourly decimal fraction of traffic each hour
```

```
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
hrlytraf = hrlydf * aadt
```

```
'calculate work zone delay without queue
```

```
'total workzone delay without queue for this hour is wzdelayhr (hrs)
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
'determine if there is a queue
```

```
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
```

```
    If queue <= 0 Then
```

```
        queue = 0
```

```
        carryover = 0
```

```
        queuedelay = 0
```

```

        iv = vii

        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

'There is a queue
Else: carryover = queue
        iv = vii
        Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover,
wzspeed)
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)

End If

totdel = totdel + totdelhr
totval = totval + totvalhr
Next num

ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel

ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval

pwuserdelay = (totval) / ((1 + dr) ^ year)
ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2
= pwuserdelay

End If

End If

'*****no pres case with duration >15
days*****

```

Case Is > 15

'Duration is longer than 15 days and work zone will be left in place overnight

pwuserdelay = 0

pwtotvalue = 0

queue = 0

carryover = 0

queuedelay = 0

wzdelay = 0

numdays = duract

totdel = 0

totval = 0

*****test for one lane bridge*****

If numlanes = 1 Then

For num = 0 To 23

hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)

hrlytraf = hrlydf * aadt * 2

wzdelayhr = (wzlength * ((2 / sl) - (1 / wzspeed))) * hrlytraf

wzdelay = wzdelay + wzdelayhr

iv = vii

Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)

totdel = totdel + totdelhr

totval = totval + totvalhr

Next num

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2
= totdel
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2
= totval
```

```
pwuserdelay = (totval) / ((1 + dr) ^ year)
```

```
ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2
= pwuserdelay
```

```
'*****no pres, duration>15, 2+
lanes*****
```

```
Else:
```

```
pwuserdelay = 0
```

```
pwtotvalue = 0
```

```
queue = 0
```

```
carryover = 0
```

```
queuedelay = 0
```

```
wzdelay = 0
```

```
For num = 0 To 23 'there are two or more lanes
```

```
'traffdist has hourly decimal fraction of traffic each hour
```

```
hrlydf = Application.WorksheetFunction.VLookup(num, traffdist, 2, False)
```

```
hrlytraf = hrlydf * aadt
```

```
'total workzone delay without queue for this hour is wzdelayhr (hrs)
```

```
wzdelayhr = (wzlength * ((2 / sl) - (1 / wszspeed))) * hrlytraf
```

```
wzdelay = wzdelay + wzdelayhr
```

```
'determine if there is a queue
```

```
queue = (hrlytraf / (numlanes - 1)) + carryover - (cap * (numlanes - 1))
```



```

    If queue <= 0 Then
        queue = 0
        carryover = 0
        queuedelay = 0
        iv = vii
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdf,
totdelhr)
    Else: carryover = queue
        iv = vii
        Call AAA(iv, numlanes, cap, sl, queue, queuel, queuedelay, carryover, wzspeed)
        Call BBB(iv, wzdelay, queuedelay, numdays, totvalhr, year, bridgeid, traffdb,
totdelhr)
    End If

```

```

    totdel = totdel + totdelhr

```

```

    totval = totval + totvalhr

```

```

Next num

```

```

    ActiveWorkbook.Worksheets("pres no pres activities").Range("o" & vii).Value2 =
totdel

```

```

    ActiveWorkbook.Worksheets("pres no pres activities").Range("p" & vii).Value2 =
totval

```

```

    pwuserdelay = (totval) / ((1 + dr) ^ year)

```

```

    ActiveWorkbook.Worksheets("pres no pres activities").Range("q" & vii).Value2 =
pwuserdelay

```

```

End If

```

```

Case Else

```

```

    MsgBox "duract did not meet case selection. Duract= " & duract

```

```

End Select

End If 'for test of duration of activity not equal zero

End If 'for test of adjusted time not 0


Next vii

End Sub


Sub pnpusercostsummation(dr, age)

'adds the user delay costs for all activities over 80 year series for both preservation list and no
preservation list. Result is presudc and nopresudc.

Dim v As Long

Dim vi As Long

Dim noprestotdelcost As Double, cumnopresudc As Double

Dim prestotdelcost As Double, cumpresudc As Double

Dim nn As Long, n As Long

'*****cumulative user delay costs for preservation
case*****

cumpresudc = 0

For v = 4 To 318

    prestotdelcost = ActiveWorkbook.Worksheets("pres no pres activities").Range("i" & v).Value2

    cumpresudc = cumpresudc + prestotdelcost

Next v


ActiveWorkbook.Worksheets("pres no pres activities").Range("i244").Value2 = cumpresudc

Worksheets("Output pres-nopres").Range("b17").Value = cumpresudc


n = 105 - age

EACpresudc = (cumpresudc * dr) / (1 - (1 + dr) ^ -n)

```

```
Worksheets("Output pres-nopres").Range("b19").Value = EACpresudc
```

```
'*****cumulative user delay costs for no preservation case  
*****
```

```
cumnopresudc = 0
```

```
For vi = 4 To 318
```

```
    noprestotdelcost = ActiveWorkbook.Worksheets("pres no pres activities").Range("q" &  
vi).Value2
```

```
    cumnopresudc = cumnopresudc + noprestotdelcost
```

```
Next vi
```

```
    ActiveWorkbook.Worksheets("pres no pres activities").Range("q244").Value2 =  
cumnopresudc
```

```
    Worksheets("Output pres-nopres").Range("d17").Value = cumnopresudc
```

```
    nn = 105 - age
```

```
'Calculate EAC for no preservation option
```

```
EACnopresudc = (cumnopresudc * dr) / (1 - (1 + dr) ^ -nn)
```

```
'write equivalent annual cost of cumulative udc (udc) to output page
```

```
Worksheets("output pres-nopres").Range("d19").Value = EACnopresudc
```

```
End Sub
```