APPENDIX D

Procedure to Quantify Consequences of Delayed Maintenance of Bridges

Bridges are complex structures, with numerous elements that become increasingly susceptible to failure as they deteriorate. The failure of an even a single structural component of a bridge leads to high repair costs; deterioration that is serious to cause bridge closure, or outright failure of a bridge that will result in even greater agency costs, significant user delayed costs, and even loss of life in some cases. The consequences of delaying bridge maintenance are well understood, but nonetheless a challenge to quantify. The different elements on a bridge have different deterioration rates and require different maintenance actions. Evaluating the consequences of delayed maintenance on bridges demands the evaluation of individual bridge components or elements. Figure D-1 shows the recommended procedure for quantifying the effects of delaying bridge maintenance.

The steps in the process are the recommended process accounts for issues specific to bridges. The bridge procedure can be implemented using an agency's bridge management system (BMS), or other analytical procedures developed to supplement the BMS. Therefore, the process is greatly simplified for agencies that have previously implemented a BMS. The following subsections detail each of the steps in the process. An example to illustrate the process further also is included in this appendix.

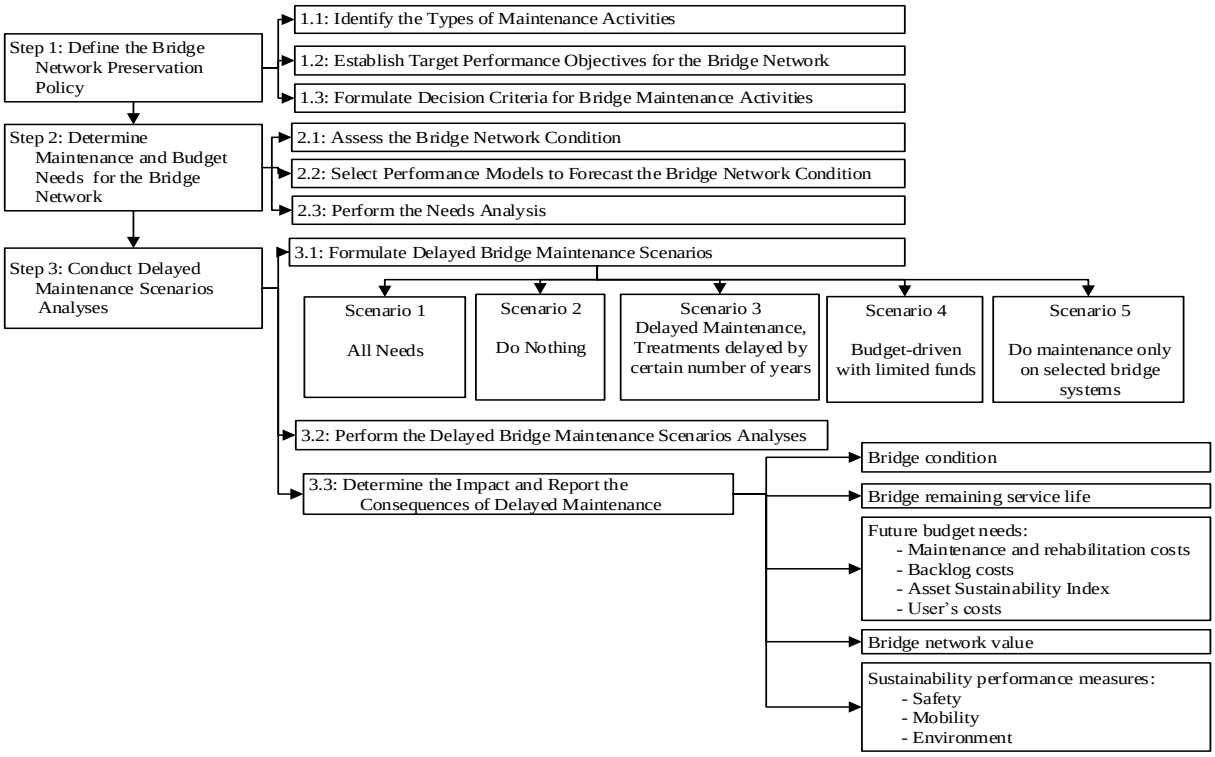


Figure D-1. Procedure to quantify the consequences of delayed maintenance of bridges.

D.1 Step 1: Define the Bridge Network Preservation Policy

D.1.1 Identify the Types of Maintenance Activities

In this step, the agency must determine what maintenance activities should be included in the preservation program. FHWA's general definitions for routine and preventive maintenance activities, which apply to all highway assets, are found in Chapter 3. In practice, maintenance activities often are defined differently across agencies. Common maintenance terms that refer specifically to bridges in the context of this research are:

Bridge preservation—"Actions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good condition; and extend their life" (FHWA 2011). Bridge preservation includes cyclical preventive maintenance, condition-based maintenance, and rehabilitation. (FHWA 2011)

Cyclical preventive maintenance—Activities "performed on a pre-determined interval and aimed to preserve existing bridge element or component conditions. Bridge element or component conditions are not always directly improved as a result of these activities, but deterioration is expected to be delayed." (FHWA 2011). Table D-1 shows examples of cyclical preventive maintenance activities.

Table D-1. Bridge cyclical preventive maintenance activities.

Cyclical PM Activity Examples	Commonly Used Frequencies (Years)
Wash/clean bridge decks or entire bridge	1 to 2
Install deck overlay on concrete decks such as: • Thin bonded polymer system overlays • Asphalt overlays with waterproof membrane • Rigid overlays such as silica fume and latex modified	 10 to 15 10 to 15 20 to 25
Seal concrete decks with waterproofing penetrating sealant	3 to 5
Zone coat steel beam/girder ends	10 to 15
Lubricate bearing devices	2 to 4

Source: FHWA 2011

It is observed that while the FHWA Bridge Preservation Guide (FHWA 2011) describes the activities in Table D-1 as cyclical, in many cases these activities can be instead performed based on condition.

Condition-based preventive maintenance is defined as "activities that are performed on bridge elements as needed and identified through the bridge inspection process." (FHWA 2011). These activities include cleaning and resealing deck joints, installing deck overlays, replacement of edge beams or expansion joints, spalls patching, structural steel painting, pressure washing or painting of concrete members, installation of scour countermeasures, fracture critical retrofit, deck overlay, deck hydro-demolition, or full deck replacement (GDOT 2013).

Rehabilitation "involves major work required to restore the structural integrity of a bridge as well as work necessary to correct major safety defects" (FHWA 2011). Often if needed rehabilitation work is not performed, a bridge may become Structurally Deficient and/or it may become necessary to replace the bridge.

As the foregoing discussion indicates, the definitions of different types of activities incorporate consideration of both the nature of the activity and the intent of performing that activity. Thus, an activity such as a deck overlay may be described as "preservation," "cyclical preventive maintenance," "condition-based preventive maintenance" or even "rehabilitation" depending on the motivation for performing the overlay and extent of other work performed on a bridge at the same time.

It is recommended that an agency review the different preservation activities performed on its bridges, as well as the definitions above, and decide what activities may or may not be considered as deferred in the event that bridge maintenance is delayed. For analyzing the effects of delaying maintenance, it is recommended that all bridge preservation-related activities short of complete rehabilitation of a bridge may be considered as deferred

if maintenance is delayed. This includes rehabilitation of individual elements or components (deck, superstructure, and substructure) but excludes overall bridge rehabilitation, bridge replacement, and functional improvements such as widening, raising and strengthening bridges. However, if an agency has established definitions for what constitutes bridge maintenance, then those definitions can instead be applied for the purpose of the analysis of delaying maintenance.

D.1.2 Establish Performance Objectives for the Bridge Network

Agencies establish performance target objectives when formulating their preservation programs. In selecting bridge performance measures it is important to consider the different factors that contribute to bridge performance, such as structural condition, functionality, structural integrity, and costs to agency and users (Hooks and Frangopol 2013). Table D-2 shows bridge performance categories with contributing factors.

Table D-2. Bridge performance categories and contributing factors.

Category	Contributing Factor
Structural condition- durability and serviceability	Structure type Structural materials and material specifications Structure age As-built material qualities and current conditions As-built construction qualities and current conditions Truck loads and other live loads Environment - climate, air quality, and marine atmosphere Snow and ice removal operations Type, timing, and effectiveness of preventive maintenance Type, timing, and effectiveness of restorative maintenance and minor and major rehabilitation Flooding, hydraulic design, and scour mitigation measures Subsurface soil characteristics – settlement
Functionality- user safety and level of service	Structure geometry - clear deck width, skew, and approach roadway alignment Design load Vertical clearances - over and under Traffic volumes and percentage of trucks Posted speed Accelerated construction to rehabilitate or replace the bridge
Structural integrity- safety and stability in all failure modes	Seismic performance Hurricane and flood resistance Collision impacts Blast impacts Fire resistance Structural redundancy and load redistribution
Cost to agency and users	Agency: Initial construction costs Agency: Maintenance, repair, and rehabilitation costs, Traffic maintenance costs Users: Accident cost Users: Detour and delay costs

Source: After LTBP Bridge Performance Primer, Hooks and Frangopol 2013

Common bridge performance measures are shown in Table D-3. Further discussion of the different measures and their use is in the contractor's report for NCHRP 20-24(37) E (Spy Pond Partners et al. 2010).

Table D-3. Examples of common performance measures for bridges.

Performance Measure	Description
NBI General Condition Rating	0 (worst) – 9 (best) rating reported for deck, substructure, and superstructure condition (and for culverts long enough to be included in the NBI).
NBI Structural Condition Rating	Good, fair, or poor, calculated based on NBI condition and appraisal ratings.
National Bridge Inventory (NBI) Structurally Deficient (SD) / Functionally Obsolete (FO) Status	Calculated based on NBI data. A bridge that is Structurally Deficient (SD) has a condition rating of 4 or less for either the deck, superstructure, or substructure (or culvert in the case of NBI-length culverts). Such bridges require rehabilitation but are not necessarily unsafe. A bridge that is FO fails to meet current functional standards for deck geometry, load-carrying capacity, clearances and/or approach roadway alignment.
Sufficiency Rating (SR)	"0 (worst) –100 (best) scale based on four factors reflecting ability to remain in service": structural adequacy and safety, serviceability and functional obsolescence, essentiality for public use, and special reductions. Calculated based on NBI data.
Element condition	Conditions for individual elements (e.g., the NBE) are summarized by percent of element quantity by state, typically with four condition states defined for an element.
Bridge Health Index (BHI)	0 (worst) – 100 (best) scale based on element condition data.

Source: after NCHRP Report 551, Cambridge Systematics, Inc. et al. 2006

On the national level, prior to passage of MAP-21, Sufficiency Rating (SR) and Structurally Deficient/ Functional Obsolete (SD/FO) status were used to determine eligibility for the Highway Bridge Replacement and Rehabilitation Program (HBRRP) (FHWA 1992). SR is a weighted average comprised calculated by combining scores for structural adequacy and safety (55 percent weight), serviceability and functional obsolescence (30 percent weight), essentiality for public use (15 percent weight), and special reductions (6 percent weight). Sufficiency Rating (SR) ranges between 0 for an entirely deficient bridge and 100 for an entirely sufficient bridge. The calculation of this measure is detailed in the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (FHWA 1995). With passage of MAP-21 the HBRRP was discontinued, though FHWA continues to calculate SR and Structurally Deficient/Functional Obsolete (SD/FO) status. While Functionally Obsolete status is no longer used as a criterion for state funding eligibility, as of 2016 this measure was still being calculated for federally owned bridges, and was being used in a number of states for their reporting. As of 2016 FHWA was in the process of developing rules for state DOTs to use for reporting bridge conditions for NHS bridges as part of their asset management plans. Further, MAP-21 sets a target for percent of bridges classified as Structurally Deficient (SD) (weighted by deck area).

Another performance measure frequently used for characterizing bridge conditions is the BHI developed by California DOT for bridge structural health assessment. BHI is calculated using Equation D-1 (Hooks and Frangopol 2013).

$$\text{BridgeHealthIndex} = (\sum QCS_i \times WF_i)/(\sum TEQ_i \times We) \qquad \textit{D-1}$$

where QCS_i = Quantity in condition state *i*
WF = Weighting factor for condition *i*
TEQ_i = Total element value *i*
We = Element indicator cost of other important indicator for each element

The decision of what bridge performance measures to include in the analysis should be made considering what data are available, the agency's analysis capabilities, what measures may have been established for other types of analysis, and what measures are required to help provide a comprehensive view of the effects of delayed maintenance. A single condition index is often not sufficient to describe the bridge performance; therefore a set of performance measures is often recommended (Robert et al. 2002).

It is recommended that the performance measures selected to express the objectives include at least one measure of physical condition, such as percent of bridges classified as Structurally Deficient, and at least one measure incorporating investment needs, such as the increase in overall bridge backlog costs caused by delaying maintenance. Definitions of common performance measures were provided in Table D-2, and the following are recommended to establish objectives:

- Percent of bridges in good, fair, and poor condition, where good/fair/poor conditions are defined based on NBI condition ratings
- Percent of bridges classified as Structurally Deficient (SD)
- Percent of bridges classified as Structurally Deficient (SD) or Functionally Obsolete (FO)
- Average Sufficiency Rating (SR)
- Average Bridge Health Index (BHI)
- Number of posted bridges
- Percent deck area with floor condition 1 or 2, on scale 1 (best) to 4 (worst) (ODOT 2008)
- Percent deck area with wearing surface of 1 or 2, on scale 1 (best) to 4 (worst) (ODOT 2008)
- Percent deck area with paint condition ≥ 5, on scale 0 (worst) to 9 (best) (ODOT 2008)

Once an agency has established target objectives (e.g. for their asset management plan), these should be considered in a gap analysis to compare projected performance with the targets. One issue related to setting performance objectives is that of how to calculate overall performance given bridge-level results. Typically results for the overall condition (e.g., percent of bridges classified as Structurally Deficient) are weighted by bridge deck area to account for this disproportionate costs associated with addressing needs for larger bridges.

D.1.3 Formulate Decision Criteria for Bridge Maintenance Activities

This step involves determining what maintenance activities should be considered as feasible for a bridge and its structural elements. The decision criteria should specify what activities are needed based on the bridge/element condition and their cost. In addition, this step should consider the treatment timing. That is some lower cost treatments can extend bridge life significantly, but these treatments must be performed in a timely fashion or their benefits will not be realized. Moreover, as a bridge deteriorates, the window for such treatment closes. For instance, joint repair prevents water seeping into the bridge substructure, but only if it is performed in a timely manner. Likewise, spot painting can extend the life of steel components, but is not feasible if the area requiring painting is too extensive or if the steel has experienced section loss.

If an agency has implemented a BMS then this information may already be specified in the BMS database. If an agency has not implemented a BMS, or not used their BMS to model maintenance activities, then it may be necessary to define them. These should be defined either for the bridge deck, superstructure and substructure, or for individual elements.

The AASHTO Guide Manual for Bridge Element Inspection (2013) defines condition states for all NBE based on distress severity, as well as feasible actions. Table D-4 shows the activities typically defined for the AASHTO NBE.

Table D-4. AASHTO condition states and feasible preservation actions.

Condition State	Description	Commonly Employed Feasible Actions
1	Good	Preventive Maintenance
2	Fair	Preventive Maintenance or Repairs
3	Poor	Rehabilitation
4	Severe	Rehabilitation or Replacement

Source: AASHTO 2013 and FHWA 2011

Tables D-5.a, D.5.b, and D.5.c show examples of relating condition to feasible maintenance activities for a particular bridge element. Since the scope and detail of preservation activities is expected to differ among agencies, AASHTO (2013) lists the feasible actions in general terms.

Table D-5a. Example of condition state definitions and feasible actions for steel truss (Element 120).

Feasible Actions / Defects	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	Do nothing Protect	Do nothing Protect Repair	Do nothing Protect Repair Rehabilitate Replace	Do nothing Protect Repair Rehabilitate Replace
Corrosion	None	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Cracking	None	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant a structural review.	
Distortion	None.	Distortion not requiring mitigation or mitigated distortion.	Distortion that requires mitigation that has not been addressed but does not warrant structural review.	
Damage	Do nothing Protect	Do nothing Protect Repair	Do nothing Protect Repair Rehabilitate Replace	Do nothing Protect Repair Rehabilitate Replace

Source: AASHTO 2013

Table D-5b. Example of condition state definitions and feasible actions for steel deck with concrete filled grid (Element 29).

Feasible Actions / Defects	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	Do nothing Protect	Do nothing Protect Repair	Do nothing Protect Repair Rehabilitate Replace	Do nothing Protect Repair Rehabilitate Replace
Corrosion	None	Freckled rust. Corrosion of the steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Cracking	None	Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar.	Identified crack that is not arrested but does not warrant structural review.	
Connection	Connection is in place and functioning as intended	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant a structural review.	
Damage	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Source: AASHTO 2013

In addition to condition-based maintenance actions, cyclical preventive maintenance activities (e.g., deck washing) may be performed regardless of bridge condition. However, these activities are not typically modeled in a BMS because they are not triggered based on a particular condition. In many models, the deterioration curves assume that the cyclical maintenance activities are performed at historic levels, without knowing how those activities influence the curve. Therefore, the curves are built on aggregation of time-data series from many assets, and some of which received cyclical maintenance and some did not. Since historic maintenance records may be poor for these activities, the analysts cannot filter between assets that did and did not receive the treatments. If this is the case for model development, and if the cyclical maintenance is performed at a higher or lower level than was done in the past, it can lead to increased disparity between projected and actual conditions. Besides, the life extension provided by these actions is not well established in the literature.

The approach described below illustrates how this can be addressed by explicitly modeling two different scenarios with different deterioration rates, with greater deterioration projected when required cyclical activities are omitted. Defining feasible preservation activities or actions is also necessary to determine when to rescope an activity. For instance, if preservation activities are defined based on condition ratings for the bridge deck, superstructure, and substructure; it is typical to specify that maintenance actions should ideally be performed for a condition rating of 5 or 6, but more extensive rehabilitation is required if the rating drops to a 4 or less. Table D-6 illustrates this approach, summarizing the feasible actions defined for different NBI condition ratings.

Table D-5c. Example of condition state definitions and feasible actions for timber deck (Element 30).

Feasible Actions / Defects	Condition State 1	Condition State 2	Condition State 3	Condition State 4
	Do nothing. Protect.	Do nothing Protect Repair	Do nothing Protect Repair Rehabilitate Replace	Do nothing Protect Repair Rehabilitate Replace
Connection	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets or fasteners; broken welds; or pack rust with distortion but does not warrant a structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Decay/Section Loss	None.	Affects less than 10 percent of the member section.	Affects 10 percent or more of the member but does not warrant structural review.	
Check/Shake	Surface penetration less than 5 percent of the member thickness regardless of location.	Penetrates 5percent-50 percent of the thickness of the member and not in a tension zone.	Penetrates more than 50 percent of the thickness of the member or more than 5 percent of the member thickness in a tension zone. Does not warrant structural review.	
Crack (Timber)	None.	Crack that has been arrested through effective measures.	Identified crack that is not arrested but does not warrant structural review.	
Split/ Delamination (Timber)	None.	Length less than the member depth or arrested with effective actions taken to mitigate.	Length equal to or greater than the member depth but does not require structural review.	
Abrasion/Wear (Timber)	None or no measurable section loss.	Section loss less than 10 percent of the member thickness.	Section loss 10 percent or more of the member thickness but does not warrant structural review.	

Source: AASHTO 2013

Similarly if using a BMS such as AASHTOWare BrM, it may be necessary to specify threshold conditions when a complete bridge rehabilitation is required, and/or scoping rules that account for physical interconnections of different elements (Robert et al. 2002). For instance, one might specify that bridge rehabilitation is required in the event the BHI of a bridge drops below certain value, or that intervention is also required on the bridge joints whenever work is performed on a deck.

Table D-6. NBI general condition rating and feasible actions.

Rating	Description	Commonly Employed Feasible Actions
9	Excellent Condition	Preventive Maintenance
8	Very Good Condition- no problems noted	
7	Good Condition- some minor problems	
6	Satisfactory Condition	Preventive Maintenance and/or Repairs
5	Fair Condition	
4	Poor Condition	Rehabilitation or Replacement
3	Serious Condition	
2	Critical Condition	
1	"Imminent" Failure Condition	
0	Failed Condition	

Source: FHWA 2011

D.2 Step 2: Determine Maintenance and Budget Needs for the Bridge Network

D.2.1 Assess the Bridge Network Condition

In this step, the agency must determine what methodology to use for assessing the bridge condition. Given that all U.S. agencies must report NBI data for their highway bridges, and recently began reporting element-level data for bridges on the NHS, an agency must determine whether to assess conditions based on NBI condition ratings or element-level data. Typically, if BMS is used to perform the analysis, the BMS will assess conditions using element-level data, as this provides a detailed view of bridge conditions, and allows for greater refinement in specifying maintenance activities. However, if an agency has developed an analytical approach outside of its BMS, or has not implemented its BMS, then it is recommended to base the condition assessment methodology on component-level condition ratings (deck, superstructure, and substructure).

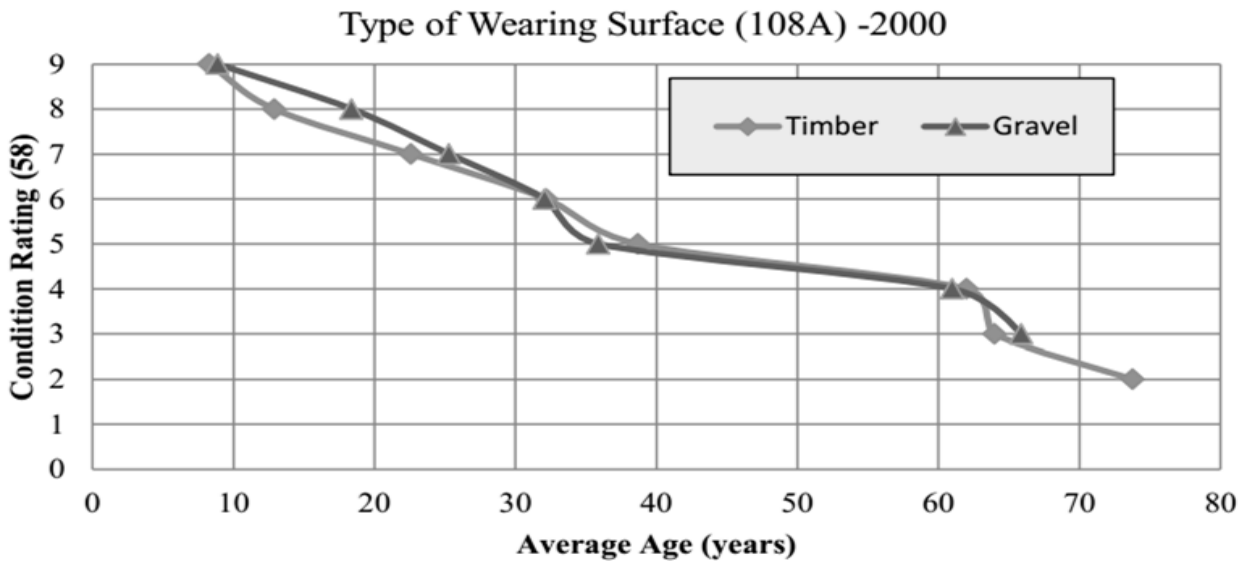
The AASHTO Guide Manual for Bridge Element Inspection (2013) described previously details how to assess condition for each National Bridge Element (NBE); and the FHWA National Bridge Inventory (NBI) Coding Guide (1995) explains how to assess conditions using general condition ratings. The FHWA's requirements for element-level inspections still strictly apply to NHS bridges.

D.2.2 Select Performance Models to Forecast the Bridge Network Condition

In this step, the agency must establish performance models that specify how the bridge components or elements will deteriorate over time, and what the impacts of any bridge preservation activities are (FHWA 2014b). Common practice for bridge components or element-level models is to define probabilistic models that specify the likelihood of transition from a rating value (if using condition ratings) or condition state (if using element data) depending on what activity, if any, is performed (NDOR 2011). The set of probabilities describing all of the possible rating/condition values, feasible activities and their probabilities of transition to other condition ratings states is referred to as transition probability matrix.

When a BMS is used to support the analysis the BMS is typically populated with a default set of probability matrices, but these should be carefully reviewed by the agency for consistency. If the agency is not using a BMS to support the analysis, then additional work is required to define either a set of transition probability matrices, or an equivalent set of models to predict bridge performance.

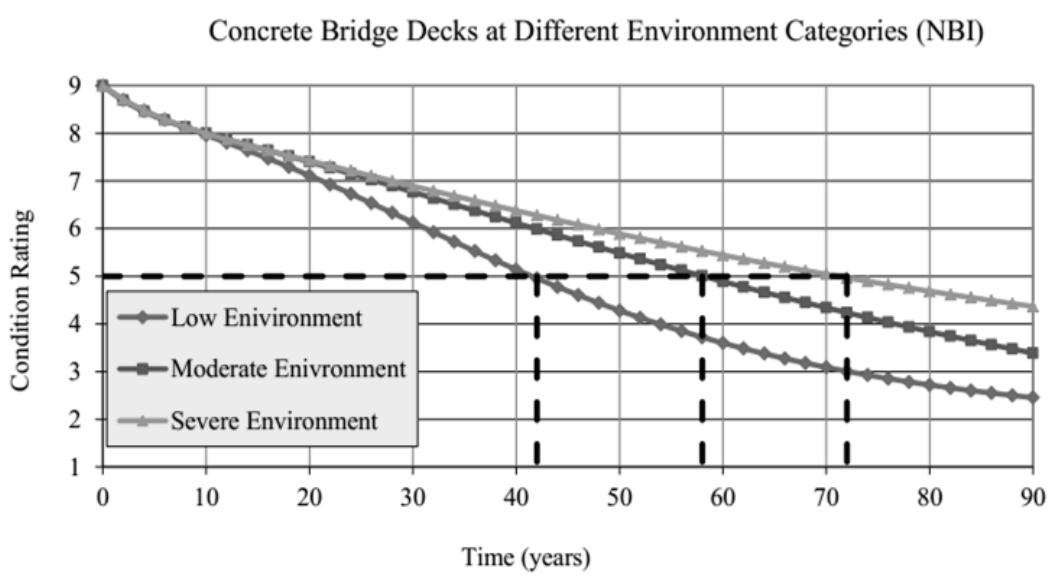
Another approach is to develop a deterministic deterioration curve. Figure D-2 shows examples of deterioration curves for timber and gravel surface, which was developed by analyzing average bridge conditions over time.



Source: NDOR 2011

Figure D-2. Deterioration curve for timber and gravel wearing surface types.

It is often helpful to develop different deterioration curves depending on traffic, climate, or other factors. Figure D-3 shows example curves for concrete bridge decks in low, moderate, and severe environments. In this example, low environment refers to average daily traffic (ADT) less than 1,000 and average daily truck traffic (truck ADT) less than 100. Moderate environment refers to ADT more than 1,000 but less than 5,000, and truck ADT more than 100 but less than 500. Severe environment refers to ADT more than 5,000, and truck ADT more than 500 (NDOR 2011).



Source: NDOR 2011

Figure D-3. Deterioration curves at different environment categories for concrete bridge decks (NBI rating format).

D.2.3 Perform the Needs Analysis

In this step, the agency must use the set of feasible preservation activities determined previously, along with the performance to determine what treatments should be performed assuming optimal maintenance. In a BMS this step is automated, and typically performed through an optimization process that determines the "optimal preservation policy" or a set of activities in order to minimize lifecycle costs. Where a BMS is not used, an agency can test different strategies to confirm the best maintenance strategy for its bridges. Once the policy/strategy has been established, then it is applied to the bridge inventory to establish initial bridge maintenance needs. This is the preferred or baseline scenario used to quantify the costs, bridge condition, and other performance measures when maintenance is performed as scheduled.

D.3 Step 3: Conduct Analysis of Delayed Bridge Maintenance Scenarios

D.3.1 Formulate Delayed Bridge Maintenance Scenarios

The needs analysis provides the baseline scenario since there are sufficient funds to implement the agency's preferred maintenance plan. Delayed maintenance scenarios are compared with the baseline scenario to quantify the consequences. A "do nothing" or no maintenance scenario is defined to provide, through comparison with the baseline maintenance scenario, quantification of the major effects of delaying maintenance. It is recommended that this scenario extend for a minimum period of 10 years, and that the maintenance budget be eliminated in this scenario, while any planned rehabilitation or replacement work is modeled as planned.

Depending on the specific issues and context that an agency faces, they may wish to define additional scenarios with alternative timeframes or maintenance strategies. For instance, an agency may prefer to extend the analysis out to a period of 20 years or longer and create the following scenarios:

- Maintenance activities are performed only for selected bridge systems (e.g., interstates or NHS)
- Maintenance activities are performed only above a threshold benefit/cost ratio or below a threshold condition.
- Maintenance, rehabilitation and replacement work is performed as required to meet the performance targets.
- Cyclical maintenance actions are deferred, resulting in more rapid deterioration of elements impacted by cyclical maintenance activities (e.g., decks and joints). The impact of shifting away from a preventive maintenance strategy is modeled by creating an alternative maintenance policy that eliminates interventions for components in fair or better condition.

Therefore, there are five types of maintenance scenarios defined for bridges:

Scenario 1 All Needs: Maintenance, rehabilitation and replacement work is performed as required to meet the performance targets established by the agency. This is considered a baseline scenario to determine the maintenance activities and budget needs over the analysis period.

Scenario 2 No Preventive Maintenance: Interventions for components in fair or better condition are eliminated. The impact of shifting away from a preventive maintenance strategy is modeled by creating an alternative maintenance policy that eliminates interventions for components in fair or better condition.

Scenario 3 Delayed Maintenance: Maintenance treatments are delayed by a certain number of years; or cyclical maintenance activities are assumed to be deferred, resulting in more rapid deterioration of elements impacted by cyclical maintenance activities (e.g., decks and joints); or maintenance activities are performed only above a threshold benefit/cost ratio or below a threshold condition.

Scenario 4 Budget-driven with limited funds for maintenance.

Scenario 5: Do maintenance only on selected bridge systems.

Table D-7 shows a summary of the key elements needed to analyze the delayed maintenance scenarios for bridges.

Table D-7. Key elements to analyze delayed maintenance scenarios for bridges.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 20 years (*)	Results
Bridge network inventory with condition assessment NBI data for all 50 states NBIAS default costs	Probabilistic-Markov models NBIAS default deterioration models NCHRP Report 713 (deck, super-structure and substructure deterioration models by state)	1. All Needs 2. No Preventive Maintenance 3. Delayed Maintenance: a. Maintenance treatments are delayed by 10 years. b. Maintenance treatments are delayed by 10 years. c. Cyclical maintenance delayed. 4. Budget-driven with limited funds for maintenance 5. Do maintenance only on selected bridge systems 6. Do maintenance only for selected benefit/cost ratio or below threshold condition.	Analytical Tools: Bridge databases and analytical tools are listed in Table D-8 as a reference. NBIAS is one of the common analytical tools used by DOTs. In-house Bridge Management Systems available at the highway agency. Table D-8 shows other databases and analytical tools. Reports**:** • Agency costs over time • Impact on bridge network condition • Change in deferred maintenance costs over time • Changes in the bridge network value and Bridge Sustainability Ratio • Changes in sustainability and user's costs

Note: Maintenance policies should be developed considering the full lifecycle of a bridge, regardless of the analysis period, and when that analysis is performed it includes bridges with a range of ages.

(*) NBIAS can be run for a period of up to 30 years. 20 years is recommended since FHWA uses this period for the analysis of bridge performance.

D.3.2 Perform the Delayed Bridge Maintenance Scenario Analysis

Performing the delayed maintenance scenarios analysis requires the following process:

- Determine the bridge conditions at the beginning of each year of the analysis period to establish needed maintenance work.
- Prioritize what maintenance work will be performed based on available funds.
- Determine the impact of funded work on bridge conditions, including maintenance work and any other rehabilitation/replacement work.
- Determine the impact on the bridge network condition.
- Tabulate the performance measures selected by the highway agency.
- Calculate the investment needs.
- Calculate the gap between predicted and targeted performance.

Table D-8 shows examples of databases and tools developed for FHWA, AASHTO and other organizations that can be used to perform delayed maintenance scenarios analysis.

Table D-8. Examples of databases and analytical tools for bridges.

Database/Tools	Description
National Bridge Investment Analysis System (NBIAS), FHWA	• Uses national bridge data from the NBI database, and offers bridge element–level maintenance simulation capabilities. • Forecasts more than 200 measures of bridge performance (including Bridge Health Index, Sufficiency Rating, and Structurally Deficient/Functionally Obsolete Status) over a multi-year period for a range of budgeting levels and the objective of minimizing lifecycle costs.
AASHTOware Bridge Management (formerly Pontis), AASHTO	• Stores bridge inspection and inventory data (at the bridge element level), tracks preservation and maintenance, predicts future bridge conditions and incorporates multi-objective optimization analysis on bridge element level for the most cost-effective bridge preservation.
Bridge Lifecycle Cost Analysis (BLCCA), NCHRP	• Uses National Bridge Inventory General Condition Rating. • Lifecycle analysis for bridges, bridges including agency and user costs. • Agency costs from routine maintenance, rehabilitation, and element/ bridge replacement. • User costs from detour, crash, and bridge work.
Project Level Analysis Tool (PLAT), FDOT	• Excel spreadsheet model to complement Pontis (now AASHTOware Bridge Management) on the project level. • Dashboard style, uses diminishing marginal returns and incremental benefit/cost. • Reports bridge performance, treatment needs, and allocated funding.

Sources: Cambridge Systematics 2007, USDOT 2013, Hawk 2003, and Sobanjo and Thompson. 2007.

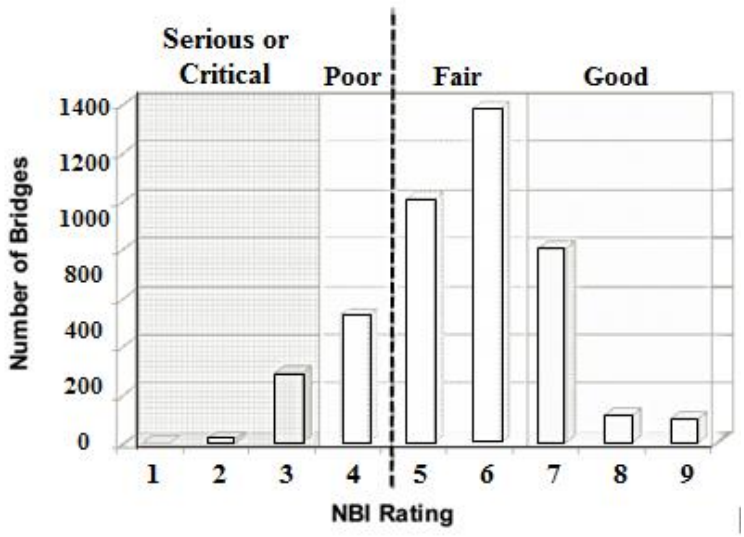
D.3.3 Determine the Impact of Delayed Maintenance and Report the Consequences

Delaying maintenance activities on bridges can have serious consequences in condition, lifecycle cost, as well as safety. For this reason, it is crucial to report the consequences of delayed maintenance on bridges to account for them in the investment decision-making process. There are different types of reports to demonstrate the consequences of delaying maintenance, some are obtained from existing BMSs and others are customized reports; a number of examples are presented in this section. The results of the scenarios analysis are used to quantify the consequences on:

- Future bridge network condition (e.g. Health Index)
- Percent of bridges classified as SD (in poor condition)
- Remaining life of the bridge network
- Future budget needs and agency costs
- Backlogged costs
- Bridge network value and sustainability ratio

Consequences on the Future Bridge Network Condition

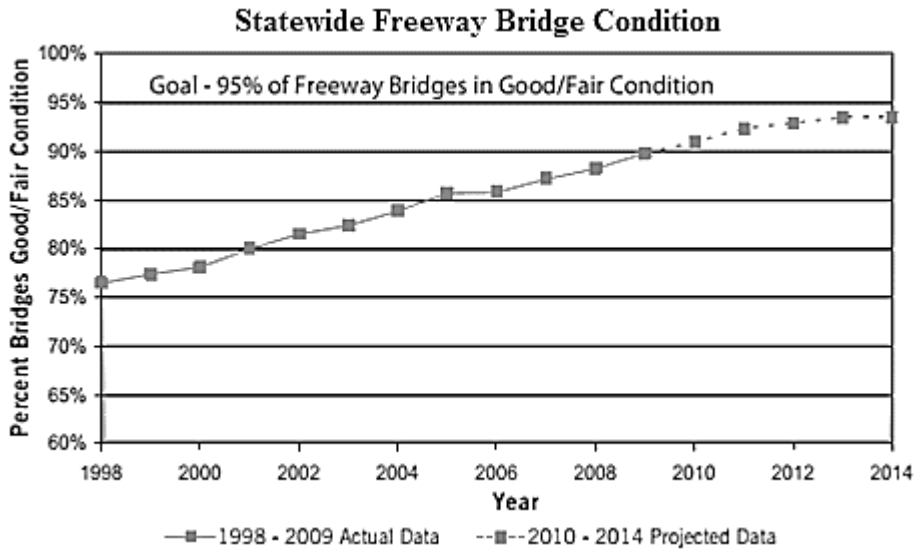
The consequences of delayed maintenance can be quantified by comparing bridge condition predictions under timely maintenance versus delayed maintenance as shown in Figures D-4 to D-9. Figure D-4 shows the NBI General Condition Rating (in this case, the minimum of the deck, superstructure and substructure ratings) with number of bridges in a specific condition category.



Adapted from: MDOT 2009a

Figure D-4. Number of Bridges by NBI General Condition Rating category.

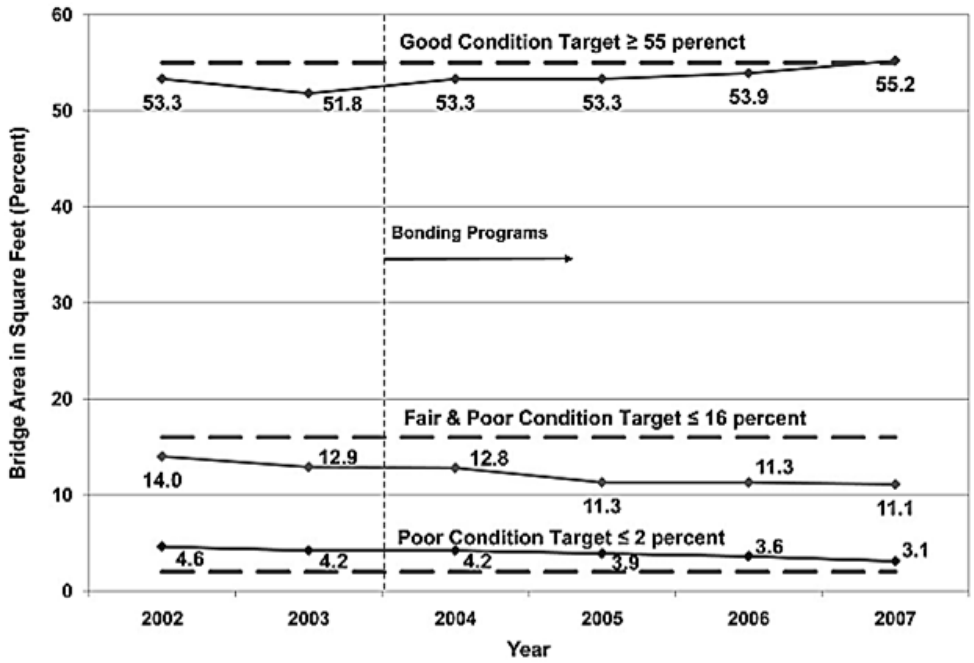
Figure D-5 shows the percentage of bridges in good/fair condition plotted together with the agency performance goal.



Adapted from: MDOT 2010

Figure D-5. Statewide freeway bridges in good and fair condition over time.

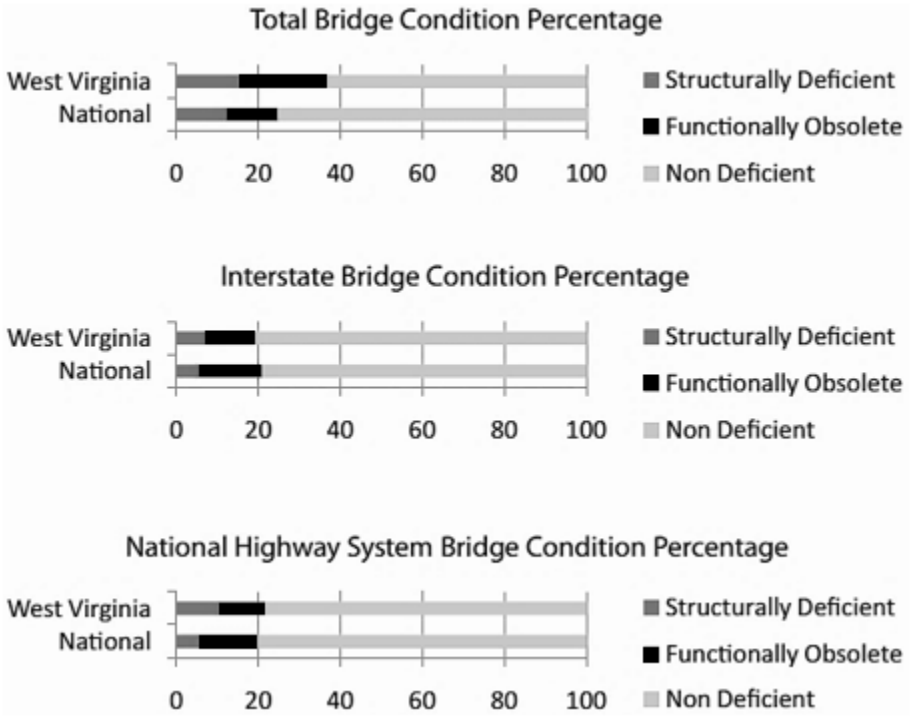
Figure D-6 shows an alternative way of plotting the percentage of bridges by condition category along with the agency target performance.



Adapted from: MDOT 2009b

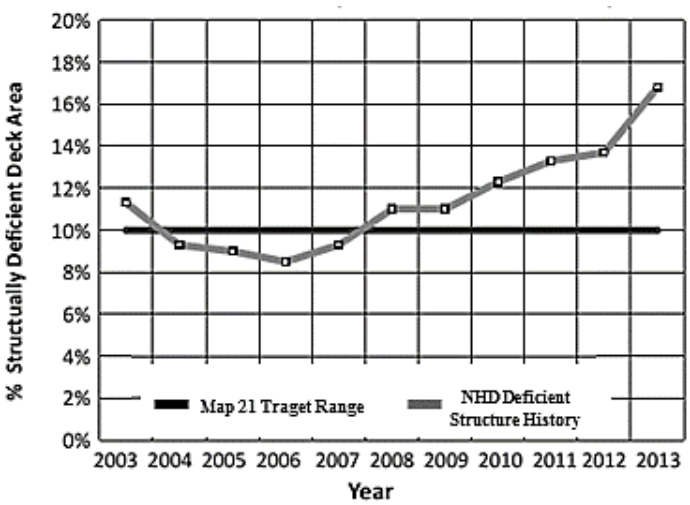
Figure D-6. Bridge condition over time compared to target performance.

Figure D-7 shows the trend of SD bridges compared to the MAP-21 target of having no more than 10 percent of bridges classified as deficient (weighted by deck area). Another approach is to report SD, FO and non-deficient bridges for a given scenario. Figure D-8 shows a comparison for state and national bridges.



Adapted from: WYDOT 2014

Figure D-7. Structurally deficient bridges history and MAP 21 target.



Adapted from: WVDOT 2012

Figure D-8. Percentage of structurally deficient and functionally obsolete bridges.

Consequences on the Remaining Service Life of the Bridge Network

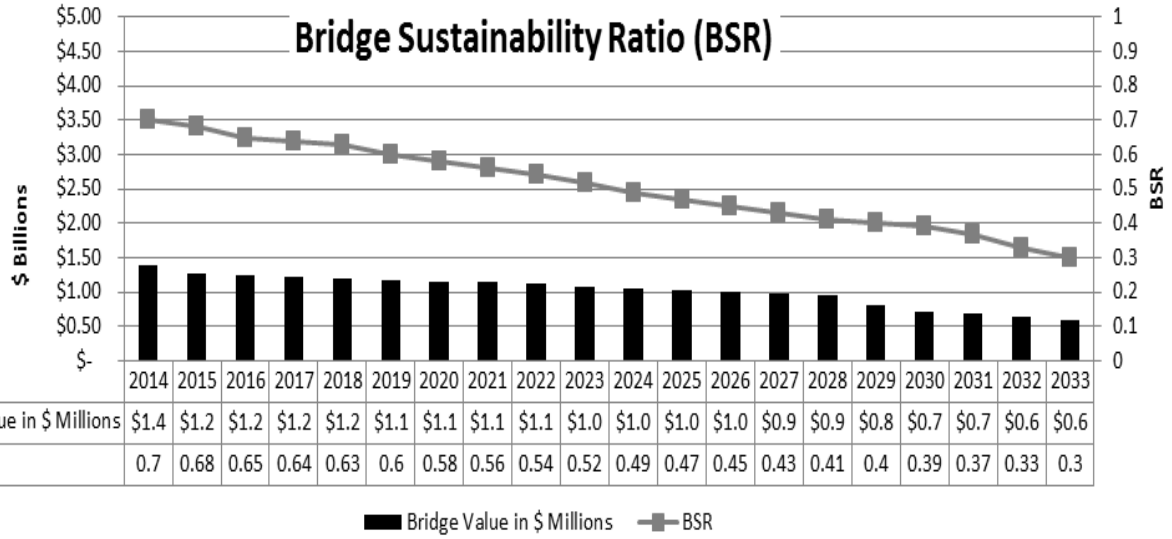
Remaining service life is a well-established concept for pavements, and it is defined as the time between the current condition and when the pavement reaches an unacceptable level of service. In the case of bridges, a remaining life definition is more complex, as each element has its own deterioration process. Therefore, bridges do not have a single service life. The effective bridge remaining life may be defined as the time until any component of the bridge reaches a condition at which the only effective treatments are to either rehabilitate or replace the bridge. Once the bridge reaches a poor condition, an agency would typically schedule bridge rehabilitation or replacement rather than maintenance actions. However, given the complexity of this issue, it is difficult to make generalized conclusions about impacts of maintenance on service life for a set of bridges. Thus, the recommended approach is to analyze representative bridges, and show for specific cases how delaying maintenance results in a shorter time until bridge replacement or rehabilitation is required. For an individual bridge, one can observe when rehabilitation or replacement is required, and compare this to the case where no maintenance work is performed. The impact on overall service life is then the reduction in years until rehabilitation or replacement is required for a bridge.

Consequences on Future Budget Needs and User Costs

If maintenance is delayed, then more costly treatments are needed to restore an acceptable condition or level of service. Agency funds needed for this purpose are estimated for the delayed maintenance scenario. Apart from the agency costs there are also significant user costs. User costs can account for travel time costs, crash costs, vehicle operating costs (VOC), and vehicle maintenance costs. Maintaining bridges in good condition prevent increases in travel time due to bridge closure detours that affects user costs. Systems such as BrM and NBIAS calculate user costs, and the increase in user costs is reported as an effect of delaying maintenance.

Consequences on the Bridge Network Asset Value

The bridge network value can be reported together with the Bridge Sustainability Ration (BSR) for a planning horizon as shown in Figure D-9. BSR is the ratio between the budget spent and funding needs to achieve the bridge network condition established by the agency.



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Bridge Value in $ Millions	$1.4	$1.2	$1.2	$1.2	$1.2	$1.1	$1.1	$1.1	$1.1	$1.0	$1.0	$1.0	$1.0	$0.9	$0.9	$0.8	$0.7	$0.7	$0.6	$0.6
BSR	0.7	0.68	0.65	0.64	0.63	0.6	0.58	0.56	0.54	0.52	0.49	0.47	0.45	0.43	0.41	0.4	0.39	0.37	0.33	0.3

Source: after FHWA 2012

Figure D-9. Bridge network value and sustainability ratio over time.

Consequences on Sustainability Performance Measures

FHWA states that a sustainable highway approach is successful when "varying objectives, including safety, mobility, environmental protection, livability, and asset management" (FHWA 2014a) are met "while working to achieve economic targets for cost-effectiveness throughout a highway's lifecycle" (FHWA 2014a). Quantifying the consequences of delayed maintenance on safety, mobility, and environment is desired. However, at the present state of knowledge, there are not direct methods to relate the deterioration of the bridge condition with this type of performance measures. The following performance measures are introduced in the bridge procedure in case the agency has the data and analytical tools to incorporate them in the analysis.

Safety Performance Measures: Risk of a bridge failure is greater for older bridges with delayed maintenance. A comparison of the outcomes of bridge maintenance scenarios can be conducted, though this is outside of the capabilities of current BMSs.

Mobility Performance Measures: The major impact on mobility for a bridge is related to lane closures during maintenance or a complete bridge closure (Butler et al. 1986). Travel time delays are caused by bottlenecks or detours, and consequences of delayed maintenance can be associated to increased travel costs.

Environmental Performance Measures: Performance measures include pollutant emissions as well as amount of hazardous waste generated by maintenance activities (Zietsman et al. 2011). Table D-9 shows an example of possible environmental impacts of bridge maintenance activities summarized by British Columbia Ministry of Transportation and Infrastructure (2010).

Table D-9. Environmental effects of bridge maintenance.

Work Activity	Potential Environmental Impacts
Cleaning	"May introduce accumulated deleterious substances (sediment, oils, de-icing chemicals, paint chips, treated wood debris) to a watercourse." "May disrupt flow, damage habitat and kill fish through the extraction of water for cleaning."
Repair Works	"May cause erosion of watercourse banks and generation of sediment if bridge abutments are not protected from draining wash water." "May disturb birds and their nests on bridge structures." "May release deleterious substances (sediment, cement-based products, wood preservatives, epoxies, mineral oils, sealants) to a watercourse." "May disturb instream and riparian habitat by changing the channel structure, banks, substrate, or vegetation." "May disturb wildlife species (e.g. birds, beavers)."
Painting	"May contaminate surface waters, groundwater, and soils through improper storage or disposal of material." "May release deleterious substances such as sediment, paints, sealants, or other chemicals to a watercourse." "May contaminate surface waters, ground water, and soils through improper storage and disposal of materials."

Source: British Columbia Ministry of Transportation and Infrastructure 2010

Example of the Procedure to Quantify the Consequences of Delayed Maintenance of Bridges

Many highway agencies have implemented their own bridge management tools to assist in the development of their preservation programs. These tools incorporate different performance measures, models, prioritization methods, and reports. This example shows how to use an existing bridge management system for quantifying consequences of delayed maintenance of bridges. The National Bridge Investment Analysis System (NBIAS) supported by the Federal Highway Administration (FHWA) is used to illustrate the application of the procedure described previously. NBIAS has information on all bridges in the United States and has been successfully used for more than 15 years. It is also user friendly and generates the information required to quantify the consequences of delayed maintenance.

D.4 Step 1: Define the Bridge Network Preservation Policy

D.4.1 Identify the Types of Maintenance in the Bridge Preservation Program

In NBIAS the term preservation refers to maintenance, repair, and rehabilitation (MR&R) activities. MR&R actions respond to bridge deterioration condition and include small maintenance activities such as bearing repair, spot painting, and deck patching, improvement activities, and major actions such as the replacement of structural elements. Maintenance activities focus on preserving the physical condition of a bridge. By contrast, improvement activities focus on enhancing a bridge's functionality (e.g. widening, raising, or strengthening). NBIAS recommends a condition-based preservation policy with the objective of minimizing agency lifecycle costs.

In this example, both preservation and improvement actions are deferred. However, in NBIAS once a bridge replacement or functional improvement is identified as a need, the need remains unchanged until met. Maintenance needs tend to increase, and if they remain unmet then it may become necessary to rehabilitate or replace the bridge. Thus, the recommended approach to show the impact of delaying maintenance is comparing delayed maintenance scenarios with the desired or baseline maintenance scenario. To tailor the analysis further, one can restrict the data to a set of bridges including maintenance candidates only and omitting those for which reconstruction or replacement is planned.

D.4.2 Establish Performance Objectives for the Bridge Network

NBIAS predicts a range of different performance measures, including NBI general condition ratings for bridge decks, superstructures and substructures, Sufficiency Rating (SR), Structurally Deficient (SD)/Functionally Obsolete (FO) Status, and Health Index (HI).

As described in the previous section, NBI condition ratings range from 9 to 0, where 9 is assigned to an element in excellent condition and 0 to an element that already failed. Bridge deck, superstructure, and substructure conditions are evaluated to obtain a NBI General Condition Index as described in Table D-10.

Table D-10. NBI General Condition Ratings.

NBI Rating	Common Actions	Description
9	Preventive maintenance	Excellent condition.
8	Preventive maintenance	Very good condition, no problems noted.
7	Preventive maintenance	Good condition, some minor problems.
6	Preventive maintenance and/or repairs	Satisfactory condition, structural elements can show some minor deterioration.
5	Preventive maintenance and/or repairs	Fair condition, all primary structural elements are sound but may have some minor section loss, cracking, spalling or scour.
4	Rehabilitation or replacement	Poor condition, advanced section loss, deterioration, spalling or scour.
3	Rehabilitation or replacement	Serious condition, loss of section, deterioration, spalling or scour have seriously affected primary structural elements.
2	Rehabilitation or replacement	Critical condition, advanced deterioration of primary structural elements. Unless closely monitored the bridge may have to be closed until corrective action is taken.
1	Rehabilitation or replacement	Imminent failure condition, major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	Replacement	Failed condition, out of service – beyond corrective action.

Source: FHWA 2011

SD status is calculated primarily based on the condition ratings. A bridge with a rating of 4 or less for the deck, superstructure or substructure is generally classified as SD. If a bridge is classified as SD then it is considered to be in poor condition.

SR ranges from 100% for an entirely sufficient bridge to 0% for an entirely deficient bridge. SR is obtained by rating five performance measures: structural adequacy, safety, serviceability, functional obsolescence, and essentiality for public (FHWA 2011). Detailed description of the SR factors is found in Recording and Coding for the Structure Inventory and Appraisal of the Nation's Bridges (FHWA 1995a). Health Index is a single indicator of the overall structural condition. It is expressed as a percentage value, with 0% for worst condition and 100% for best condition (FHWA 2010). SR and Health Index provide measures of the overall average bridge condition.

In NBIAS, the overall objective is to maximize user benefits and minimize agency costs subject to a budget constraint (or constraint on the benefit/cost ratio of work performed). This objective is met when all work needed is performed (that is, when the backlog of unmet needs is reduced to 0). With respect to preservation work, this translates into following the optimal preservation policy, as this policy by definition represents the set of actions that should be performed to minimize lifecycle costs. One can further supplement the preservation policy with business rules specifying when a bridge must be rehabilitated or replaced in its entirety.

In most cases, an agency running the system will find that it has a backlog of needs and that it may be difficult to meet all needs given projected funding. An agency can use the system to determine the funding required to achieve a certain level of performance, such as the annual budget required to keep the percent of

bridges classified as SD below a threshold value. Alternatively, an agency may find that even when all needs are met the system predicts a decline in bridge conditions. For this example, the performance objective used was the NBIAS default of reducing the backlog of unmet needs to 0.

D.4.3 Formulate Decision Criteria for Bridge Maintenance Activities

NBIAS includes a default set of models for specifying what maintenance activities are feasible by bridge element. Bridge element data may be imported into the system, but if the data are unavailable the system estimates the element composition of each bridge based on NBI data. For this example, NBIAS defaults were used for specifying maintenance activities. Also, a set of replacement rules was defined for establishing criteria for when overall bridge replacement is required rather than maintenance. Figure D-10 shows a screen shot of these rules in the system. Together they specify that a bridge should be completely rehabilitated or replaced if either its Health Index is less than 75 or its Sufficiency Rating is less than 50.

SD	FO	SR<=	HIX<=	Age>=	Description (%)
No	No	n/a	75	n/a	IF HIX <= 75% REPLACE
No	No	50	n/a	n/a	IF SR<=50% REPLACE

Figure D-10. Replacement Rules tab.

D.5 Step 2: Determine Maintenance Treatments and Budget Needs

D.5.1 Assess the Bridge Network Condition

Given that this example relies on NBI data, NBIAS is used following the NBI condition ratings to assess bridge condition, as detailed previously. Note that an agency may import element-level condition data, but in this example only NBI data have been used.

NBIAS uses National Bridge Inventory (NBI) data to establish a bridge inventory. NBIAS is designed to work with the complete nation's bridge inventory, a state bridge inventory, or a group of bridges of a particular functional class. In our example, NBIAS is run for a group of 7,359 bridges of varying design types and functional classifications.

The inventory data in NBIAS include NBI data items such as:

- Bridge location
- Bridge type
- Construction year
- District
- Full Bridge ID
- Functional class
- ADT total, year of ADT, future ADT.

Table D-11 defines the list of NBI items stored in the NBIAS database.

Table D-11. Description of NBI items.

Item #	Description	Item #	Description
1	State Code	55	Minimum Lateral Under clearance on Right
2	Highway Agency District	56	Minimum Lateral Under clearance on Left
3	County (Parish) Code	58	Deck Condition Rating
4	Place Code	59	Superstructure Condition Ratings
5	Inventory Route	60	Substructure Condition Ratings
6	Features Intersected	61	Channel and Channel Protection
7	Facility Carried by Structure	62	Culverts Condition Ratings
8	Structure Number	63	Method used to Determine Operating Rating
9	Location	64	Operating Rating
10	Inventory Route, Minimum Vertical Clearance	65	Method used to Determine Inventory Rating
11	Kilometer Point	66	Inventory Rating
12	Base highway Network	67	Structural Evaluation Appraisal Ratings
13	LRS Inventory Route, Subroute Number	68	Deck Geometry Appraisal Ratings
19	Bypass, Detour, Length	69	Under clearances, Vertical and Horizontal Appraisal Ratings
20	Toll	70	Bridge Posting
21	Maintenance Responsibility	71	Waterway Adequacy Appraisal Ratings
22	Owner	75	Type of Work
26	Functional Classification of Inventory Route	76	Length of Structure Improvement
27	Year Built	90	Inspection Date
28	Lanes On and Under the Structure	91	Designated Inspection Frequency
29	Average Daily Traffic	92	Critical Feature Inspection
30	Year of Average Daily Traffic	93	Critical Feature Inspection Date
31	Design Load	94	Bridge Improvement Cost
32	Approach Roadway Width	95	Roadway Improvement Cost
33	Bridge Median	96	Total Project Cost
34	Skew	97	Year of Improvement Cost Estimate
35	Structure Flared	98	Border Bridge
36	Traffic Safety Features	99	Border Bridge Structure Number
37	Historical Significance	100	STRAHNET Highway Designation
38	Navigation Control	101	Parallel Structure Designation
39	Navigation Vertical Clearance	102	Direction of Traffic
40	Navigation Horizontal Clearance	103	Temporary Structure Designation
41	Structure Open, Posted or Closed to Traffic	104	Highway System of the Inventory Route
42	Type of Service	105	Federal Lands Highways
43	Structure Type, Main	106	Year Reconstructed

Table D-11. Description of NBI items. (Continued)

Item #	Description	Item #	Description
44	Structure Type, Approach Spans	107	Deck Structure Type
45	Number of Spans in Main Unit	108	Wearing Surface/Protective System
46	Number of Approach Spans	109	Average Daily Truck Traffic
47	Inventory Route, Total Horizontal Clearance	110	Designated National Network
48	Length of Maximum Span	111	Pier or Abutment Protection
49	Structure Length	112	NBIS Bridge Length
50	Curb or Sidewalk Widths	113	Scour Critical Bridges
51	Bridge Roadway Width, Curb-to-Curb	114	Future Average Daily Traffic
52	Deck Width, Out-to-Out	115	Year of Future Average Daily Traffic
53	Minimum Vertical Clearance Over Bridge Roadway	116	Minimum Navigation Vertical Clearance
54	Minimum Vertical Under clearance		

D.5.2 Select Performance Models to Forecast the Bridge Network Condition

Based on NBI standards most highway bridges are inspected at least every two years. In this example, NBIAS is run with condition assessment data collected at 2-year intervals, consistent with NBI requirements. NBIAS models bridge elements using a Markovian model. For each bridge element a transition probability matrix is defined specifying the probability that a bridge element will move to (or stay in) a given condition state when a certain action is taken. Up to three actions may be defined for an element. Action 0 (Do Nothing) is always defined. Depending on the element and condition state, Action 1 (typically a minor maintenance action) and Action 2 (element rehabilitation or replacement) may or may not be defined. AASHTO default element definitions are used by the system to define elements, condition states and actions in this example.

Figure D-11 shows a screenshot from the MR&R Model tab in NBIAS illustrating a transition probability matrix. In this case, the element has 5 conditions states and all 3 actions are defined. The probabilities shown represent the probability of transition from the state indicated on the vertical axis to the state indicated on the horizontal axis given the specified action is performed. NBIAS defaults are used for all models defined in the example.

Transition Probabilities

Action 0 (do nothing)

CS	1	2	3	4	5
1	87.06	12.94			
2		93.30	6.70		
3			84.09	15.91	
4				84.09	15.91
5					79.37

Action 1

CS	1	2	3	4	5
1	97.03	2.97			
2	41.00	55.24	3.76		
3	29.50	10.50	55.77	4.23	
4	25.00	5.00	8.33	53.09	8.58
5	41.67	6.67	1.67	0.83	49.16

Action 2

CS	1	2	3	4	5
1					
2	64.21	33.74	2.05		
3	71.32	11.89	16.79		
4	74.50	8.13	0.68	16.69	
5	100.00				

Figure D-11. Example of transition probability matrices.

D.5.3 Perform the Needs Analysis

As discussed previously, in NBIAS maintenance needs are determined by applying the optimal preservation policy. This policy specifies what action should be taken to minimize lifecycle costs by element, condition state, operating environment, and climate zone. Figure D-12 shows an example of the optimization model results for a given element/operating environment/climate zone combination, with the policy listed by condition state (CS).

For each state, the screenshot shows the recommended action, unit cost, agency, user and total benefit, and benefit/cost ratio of performing the actions.

Optimization Results

CS	A	Cost	Total Benefit	Agency Benefit	User Benefit	B/C Ratio
1	0	0.00	0.00	0.00	0.00	0.000000
2	1	26.86	49.46	49.02	0.44	1.841374
3	2	164.32	303.86	302.73	1.13	1.849226
4	2	173.80	443.53	441.18	2.35	2.551966
5	2	277.28	645.82	641.65	4.17	2.329117

Figure D-12. Example of NBIAS element optimization model results.

Note that the preservation policy in and of itself provides insight into the costs of delaying maintenance. In this particular example, which is for a deck element measured in square meters, no action is recommended if the element is in State 1. Action 1 (minor maintenance) is recommended if the element is in State 2 and Action 2 (rehabilitation) is recommended if the element deteriorates to State 3, 4 or 5. Benefits, and thus the costs of delaying maintenance a year, are predicted whenever actions are recommended. For example, in State 2 the costs of performing needed maintenance are $26.86 per square meter. If work is deferred a year, then the cost will be $49.02 per square meter and user costs (from driving on a rougher bridge deck) will increase by $0.44 per square meter. The benefit of taking action relative to deferring action for a year is thus $49.02 + $0.44 - $26.86 = $22.60.

Though the element-level data is important for predicting maintenance needs, it is only one input into the overall needs prediction. The system also predicts needs resulting from the replacement rules described previously, and functional improvement needs. The overall needs are reported as an output of an NBIAS model run.

D.6 Step 3: Conduct Delayed Bridge Maintenance Scenario Analysis

D.6.1 Formulate Delayed Maintenance Scenarios

In this step, one must formulate a set of analysis scenarios. In NBIAS a single scenario may consist of a set of runs at different budget levels. Six different scenarios were formulated for this example:

Table D-12. Descriptions of scenarios runs.

Scenario	Definition	Description
1	All needs	Maintenance, rehabilitation and replacement work is performed as needed to meet the performance targets established by the agency.
2	No Preventive Maintenance Interventions for components in fair or better condition eliminated	The impact of shifting away from a preventive maintenance strategy is modeled by creating an alternative maintenance policy that eliminates interventions for components in fair or better condition.
3	Delayed maintenance treatments	
	a. 10 years delay	Maintenance treatments are delayed by 10 years.
	b. 20 years delay	Maintenance treatments are delayed by 20 years.
	c. Cyclical maintenance delayed	Cyclical maintenance actions are assumed to be deferred, resulting in more rapid deterioration of elements impacted by cyclical maintenance activities (e.g., decks and joints.
4	Budget-driven with limited funds	
	a. Maintenance $250M budget scenario	Maintenance treatments are performed assuming that there are limited funds to implement the agency's desired maintenance plan. The budget was limited to $250M/year for 20 years. Treatments are prioritized by the system based on incremental benefit/cost.
	b. Maintenance $125M budget scenario	Maintenance treatments are performed assuming that there are limited funds to implement the agency's desired maintenance plan. The budget was limited to $125M/year for 20 years. Treatments are prioritized by the system based on incremental benefit/cost.
5	Only selected bridge systems.	Maintenance treatments are performed only for selected bridge systems (e.g., interstates or NHS).
6	Only selected benefit/cost ratio or below a threshold condition.	Maintenance treatments are performed only above a threshold benefit/cost ratio or below a threshold condition.

The length of the analysis period was set to 21 years for each scenario to support quantification of the effects of delaying maintenance by 20 years. Of scenarios listed in the Table, 1 and 3 provide the most straightforward implementation of the process. By comparing Scenario 3.a to Scenario 1 the consequences of delaying maintenance are quantified for a 10-year period, and by comparing Scenario 3.b to Scenario 1 the consequences of delaying maintenance are quantified for a 20-year period. The other scenarios were run to demonstrate the feasibility of using NBIAS to address the consequences of delay for varying situations and with different underlying assumptions. However, the discussion focuses on presenting results for scenarios 1 and 3.

D.6.2 Perform the Delayed Bridge Maintenance Scenario Analysis

The NBIAS Analytical Module performs the analysis of the scenarios to quantify the consequences of delayed maintenance. Note NBIAS predicts over 200 different measures of effectiveness (MOE), which include measures of need, work performed in the scenario, and performance measures such as those described previously. Table D-13 lists the measures of effectiveness recorded for this example.

Table D-13. Measures of effectiveness used in this example.

Measure	Description
TFND	Total Federal Structural/Functional Needs
TWTD	Money Spent for Structural/Functional Needs, Annually
TFXD	Total Federal Structural/Functional Work Backlog
MRND	Total MR&R Needs (federal and local)
MRWD	Federal and Local MR&R Work Done, Annually
MRJD	Federal and Local MR&R Work Offset by Economically Motivated Replacement
MRXD	Total (Federal and Local) MR&R Work Backlog
UBOD	Total User Benefits, Obtained
UOMD	Obtained User Benefits of MR&R (federal and local)
HIXA	Average health index
SDPC	Deck area percentage of structurally deficient bridges

The following subsections document the results by scenario, with detailed information on scenarios 1, 3.a, and 3.b; and summary descriptions of the other scenarios.

D.6.3 Scenario 1 – Baseline Maintenance Scenario

In Scenario 1, there are unconstrained funds for 21 years. In this scenario, the backlog of remaining needs is $0 million at the end of the analysis period. Tables D-14 to D-19 document the results of this scenario and figures D-13 to D-17 present the results graphically.

Tables D-14 and D-15 show the total needs (TFND), total work (TWTD), backlog of needs (TFXD), MR&R needs (MRND), MR&R work done (MRWD), MR&R work offset by replacement (MRJD), MR&R backlog (MRXD), user benefits obtained (UBOD), obtained user benefits of MR&R (UOMD), health index (HIXA), and structurally deficient deck area (SDPC) under Scenario 1 for each year of the analysis. In Table D-14, the values are undiscounted and in Table D-15, the values are discounted at a rate of 7 percent. In this scenario the backlog of needs are $9,882 million after 10 years of deferred work and the $0 at the end of the analysis period. Note that bridge replacements are classified according to whether they are triggered by needs, or "economically motivated," or justified as being more cost effective than performing needed maintenance work. Functional improvements modeled by the system include raising brides, widening existing lanes and shoulders of bridges and strengthening bridges. In this scenario, all needs are met and the backlog of needs is $0 at the end of the analysis period.

Table D-14. Undiscounted MOEs by analysis year (Scenario 1).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3160	2990	297	179	178	1	0	1546	1	96	8
2016	375	219	158	74	74	0	0	1	0	97	3
2017	248	90	158	58	58	0	0	3	1	97	2
2018	229	91	137	58	58	0	0	2	1	96	2
2019	312	312	1	58	58	0	0	5	2	97	2
2020	77	75	1	58	58	0	0	3	2	96	1
2021	83	81	1	60	60	0	0	3	2	96	2

Table D-14. Undiscounted MOEs by analysis year (Scenario 1). (Continued)

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2022	79	77	1	62	62	0	0	4	3	96	3
2023	83	81	1	63	63	0	0	7	6	96	3
2024	78	80	1	64	64	0	0	8	7	96	4
2025	233	234	1	64	64	0	0	20	8	96	4
2026	74	74	0	65	65	0	0	9	9	96	5
2027	81	81	0	67	67	0	0	13	12	96	5
2028	71	71	0	68	68	0	0	13	12	96	5
2029	83	86	0	69	69	0	0	14	13	96	5
2030	83	83	0	70	70	0	0	14	13	96	0
2031	109	109	0	73	73	0	0	16	13	96	5
2032	88	82	7	75	75	0	0	14	14	96	5
2033	90	83	7	75	75	0	0	14	14	96	5
2034	98	88	10	77	77	0	0	15	14	96	5
2035	101	102	0	78	78	0	0	16	14	96	5

Table D-15. Discounted MOEs by analysis year (Scenario 1).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3160	2900	297	179	178	1	0	1546	1	96	8
2016	350	204	148	69	69	0	0	1	0	97	3
2017	216	78	138	51	51	0	0	3	0	97	2
2018	187	75	112	47	47	0	0	2	1	96	2
2019	238	238	1	44	44	0	0	4	1	97	2
2020	55	54	1	42	42	0	0	2	1	96	1
2021	55	54	1	40	40	0	0	2	2	96	2
2022	49	48	1	39	39	0	0	3	2	96	3
2023	48	47	1	37	37	0	0	4	3	96	3
2024	43	43	1	35	35	0	0	4	4	96	4
2025	118	119	1	33	33	0	0	10	4	96	4
2026	35	35	0	31	31	0	0	4	4	96	5
2027	36	36	0	30	30	0	0	6	5	96	5
2028	29	29	0	28	28	0	0	5	5	96	5
2029	32	33	0	27	27	0	0	5	5	96	5
2030	30	30	0	25	25	0	0	5	5	96	5
2031	37	37	0	25	25	0	0	5	4	96	5
2032	28	26	2	24	24	0	0	4	4	96	5
2033	27	25	2	22	22	0	0	4	4	96	5
2034	27	24	3	21	21	0	0	4	4	96	5
2035	26	26	0	20	20	0	0	4	4	96	5

Tables D-16, D-17, and D-18 show the number of bridges by rating value for the deck, superstructure, and substructure respectively. The bridge appraisal rating varies from 9 (best condition) to 0 (worst condition). The tables show that even with an unconstrained budget the system will allow some bridges to exist in poor condition (rating of 4 or less). These bridges are allowed to remain in a deficient condition because it is not cost effective to replace them based on default system parameters. Figures D-13, D-14 and D-15 present this information graphically. Note that the rating appears as "N" in cases where data were missing or otherwise insufficient for predicting future condition.

Table D-16. Number of bridges by deck rating and analysis year (Scenario 1).

Deck Rating	9	8	7	6	5	4	3	2	1	0	N
Base	19	1256	3842	1672	384	91	62	4	0	0	29
2015	1236	1337	2899	1511	273	41	21	0	0	0	41
2016	614	2414	2266	1595	370	41	18	0	0	0	41
2017	618	2164	2147	1833	493	46	17	0	0	0	41
2018	613	2063	2057	1913	605	52	15	0	0	0	41
2019	641	2011	1880	1837	867	68	14	0	0	0	41
2020	716	1930	1852	1541	1166	109	4	0	0	0	41
2021	1021	1638	1713	1379	1433	134	0	0	0	0	41
2022	1376	1289	1691	1160	1643	159	0	0	0	0	41
2023	1517	1136	1692	867	1938	168	0	0	0	0	41
2024	1529	1124	1668	716	2113	168	0	0	0	0	41
2025	1529	1127	1660	574	2253	174	1	0	0	0	41
2026	1525	1129	1657	530	2302	174	1	0	0	0	41
2027	1523	1129	1658	492	2339	175	2	0	0	0	41
2028	1524	1125	1656	464	2372	173	4	0	0	0	41
2029	1525	1128	1653	429	2406	173	4	0	0	0	41
2030	1522	1128	1656	382	2453	170	7	0	0	0	41
2031	1526	1125	1658	338	2494	170	7	0	0	0	41
2032	1525	1127	1656	292	2542	169	7	0	0	0	41
2033	1526	1129	1652	254	2584	166	7	0	0	0	41
2034	1524	1130	1654	241	2600	162	7	0	0	0	41
2035	1529	1127	1653	240	2602	160	7	0	0	0	41

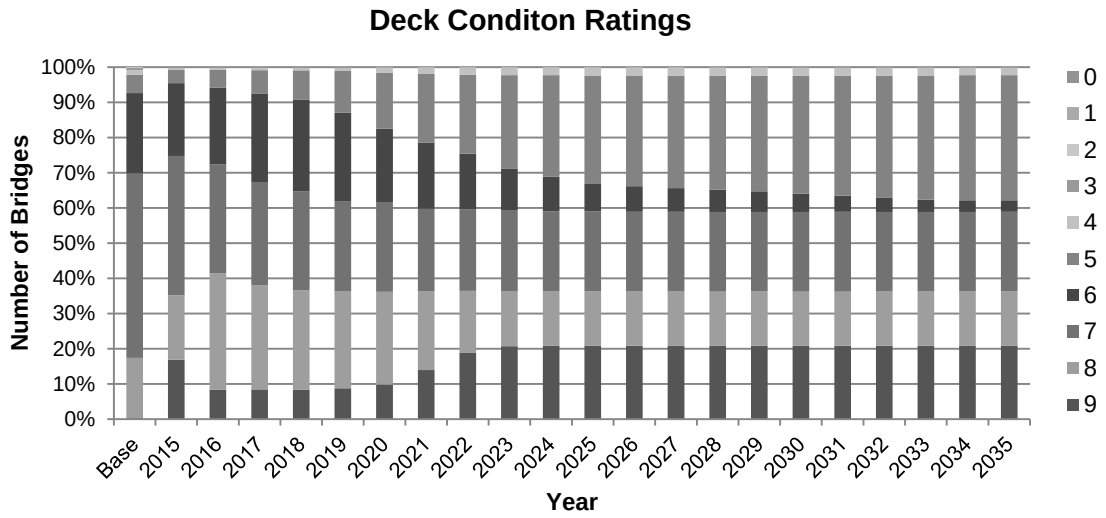


Figure D-13. Deck condition ratings over time (Scenario 1).

Table D-17. Number of bridges by superstructure rating and analysis year (Scenario 1).

Superstructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	20	1318	3682	1801	454	65	13	6	0	0	0
2015	2030	4185	821	256	63	4	0	0	0	0	0
2016	3461	3063	510	247	74	3	1	0	0	0	0
2017	3452	2951	600	255	96	4	1	0	0	0	0
2018	3475	2930	480	367	96	10	1	0	0	0	0
2019	3461	2862	540	286	188	22	0	0	0	0	0
2020	3447	2891	514	292	177	38	0	0	0	0	0
2021	3410	2874	562	310	160	43	0	0	0	0	0
2022	3374	2889	581	317	161	37	0	0	0	0	0
2023	3353	2893	587	325	56	145	0	0	0	0	0
2024	3356	2879	569	346	63	146	0	0	0	0	0
2025	3338	2881	574	345	75	146	0	0	0	0	0
2026	3335	2872	582	338	84	148	0	0	0	0	0
2027	3321	2882	577	346	81	152	0	0	0	0	0
2028	3316	2881	581	344	73	164	0	0	0	0	0
2029	3311	2886	581	342	63	176	0	0	0	0	0
2030	3306	2886	585	342	57	183	0	0	0	0	0
2031	3308	2885	586	342	56	182	0	0	0	0	0
2032	3298	2892	589	341	53	186	0	0	0	0	0
2033	3300	2889	593	341	54	182	0	0	0	0	0
2034	3290	2898	592	343	54	182	0	0	0	0	0
2035	3284	2899	595	342	57	182	0	0	0	0	0

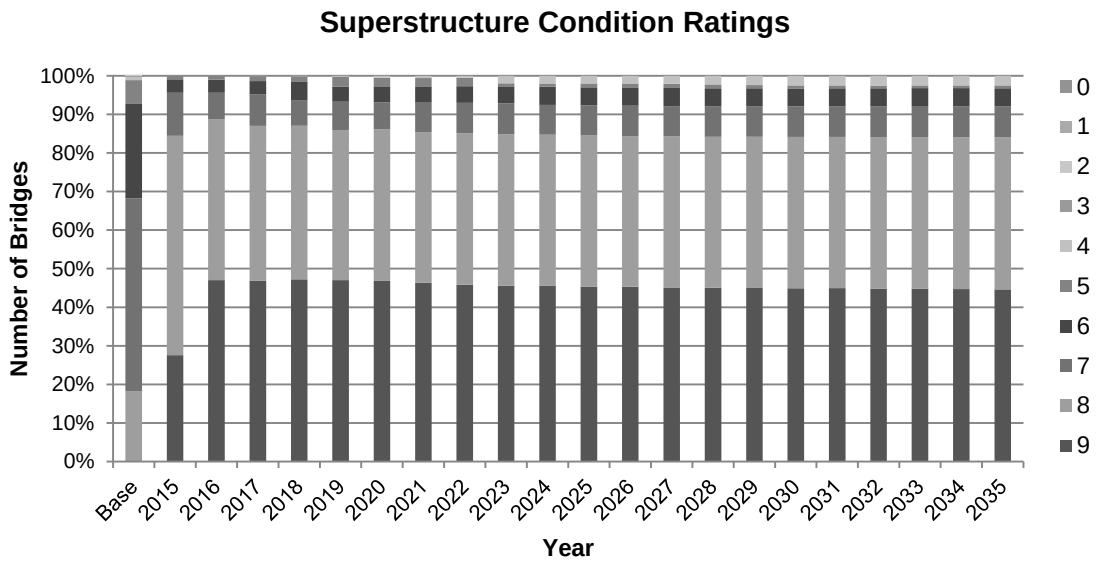


Figure D-14. Superstructure condition ratings over time (Scenario 1).

Table D-18. Number of bridges by substructure rating and analysis year (Scenario 1).

Substructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	18	1287	401	1422	467	111	25	17	1	0	0
2015	2296	4623	236	89	49	11	2	0	0	0	53
2016	5017	2084	44	95	57	8	1	0	0	0	53
2017	5183	1841	113	97	62	8	2	0	0	0	53
2018	5728	1268	59	179	60	11	1	0	0	0	53
2019	5740	1167	153	184	47	15	0	0	0	0	53
2020	5751	1159	157	102	111	26	0	0	0	0	53
2021	5763	1161	142	104	101	35	0	0	0	0	53
2022	5754	1174	112	128	95	43	0	0	0	0	53
2023	5741	1179	106	140	95	45	0	0	0	0	53
2024	5738	1148	125	150	36	109	0	0	0	0	53
2025	5739	1141	128	142	33	123	0	0	0	0	53
2026	5737	1141	122	141	44	121	0	0	0	0	53
2027	5734	1140	122	125	63	122	0	0	0	0	53
2028	5734	1137	118	127	67	123	0	0	0	0	53
2029	5734	1135	116	124	73	124	0	0	0	0	53
2030	5733	1132	117	119	77	128	0	0	0	0	53
2031	5736	1129	111	118	84	128	0	0	0	0	53
2032	5736	1127	105	126	84	128	0	0	0	0	53
2033	5739	1129	99	129	82	128	0	0	0	0	53
2034	5739	1129	93	106	109	130	0	0	0	0	53
2035	5736	1132	93	105	111	129	0	0	0	0	53

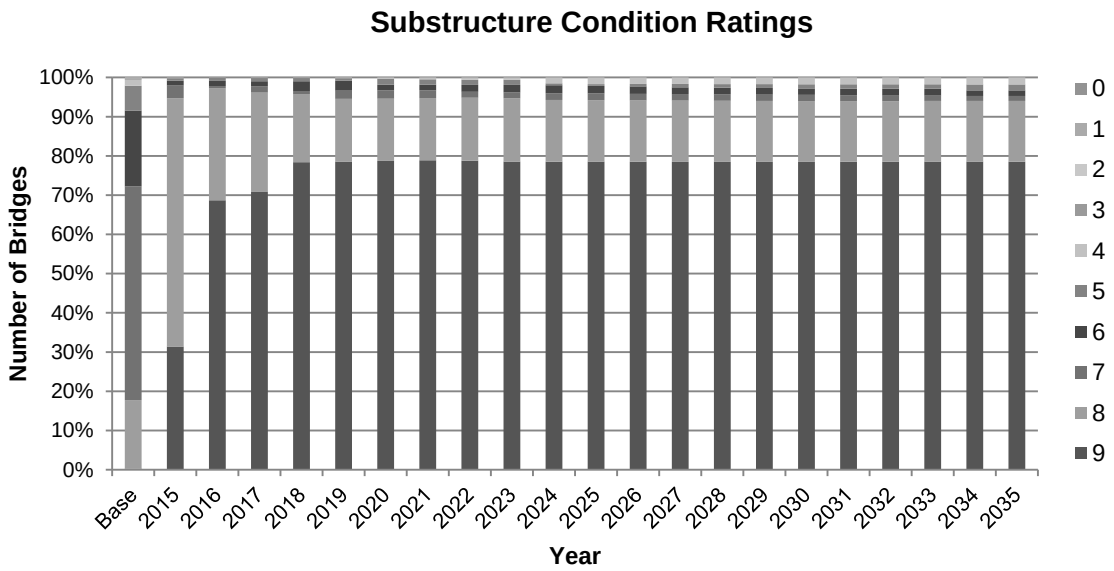


Figure D-15. Substructure condition ratings over time (Scenario 1).

Table D-19 shows predicted bridge conditions for Scenario 1. Measures shown in the table include the number of bridges in good condition (sufficiency rating (SR) > 80), fair condition (SR between 50 and 80), and poor condition (SR < 50), as well as the number of bridges that are structurally deficient (SD) and functionally obsolete (FO), the average sufficiency rating (SR), and the average Health Index (HI). Figures D-16 to D-20 present this information graphically.

Table D-19. Predicted bridge-level conditions by analysis year (Scenario 1).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.2	76.9	91.9
2015	5771	1579	9	1066	25.0	84	2.6	982	22.4	84.0	96.3
2016	5756	1598	5	1066	24.2	79	1.8	987	22.4	84.2	96.6
2017	5728	1624	7	1080	24.2	85	1.8	995	22.4	84.1	96.6
2018	5715	1633	11	1098	24.6	98	2.5	1000	22.1	84.0	96.4
2019	5653	1691	15	1125	23.8	125	1.5	1000	22.3	84.5	96.6
2020	5590	1750	19	1183	24.7	184	2.1	999	22.6	84.4	96.4
2021	5583	1766	10	1218	25.4	219	2.8	999	22.7	84.3	96.3
2022	5574	1781	4	1248	26.0	247	3.1	1001	22.9	84.2	96.2
2023	5513	1839	7	1349	26.7	367	4.0	982	22.7	83.9	96.2
2024	5475	1880	4	1405	26.8	431	4.1	974	22.7	83.8	96.1
2025	5442	1913	4	1419	25.9	452	4.6	967	21.3	84.0	96.1
2026	5417	1941	1	1419	26.4	452	5.2	967	21.3	83.8	96.0
2027	5401	1957	1	1426	26.5	459	5.2	967	21.3	83.7	96.0

Table D-19. Predicted bridge-level conditions by analysis year (Scenario 1). (Continued)

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
2028	5388	1970	1	1439	26.6	472	5.3	967	21.3	83.6	95.9
2029	5372	1985	2	1445	26.6	485	5.4	960	21.2	83.6	95.9
2030	5346	2009	4	1459	26.6	496	5.4	963	21.2	83.5	95.9
2031	5337	2020	2	1457	26.5	495	5.4	962	21.1	83.5	95.8
2032	5332	2020	7	1458	26.5	498	5.5	960	21.0	83.4	95.8
2033	5333	2021	5	1456	26.5	491	5.4	965	21.0	83.4	95.8
2034	5317	2036	6	1464	26.5	489	5.4	975	21.1	83.3	95.8
2035	5309	2046	4	1460	26.4	486	5.4	974	21.0	83.3	95.8

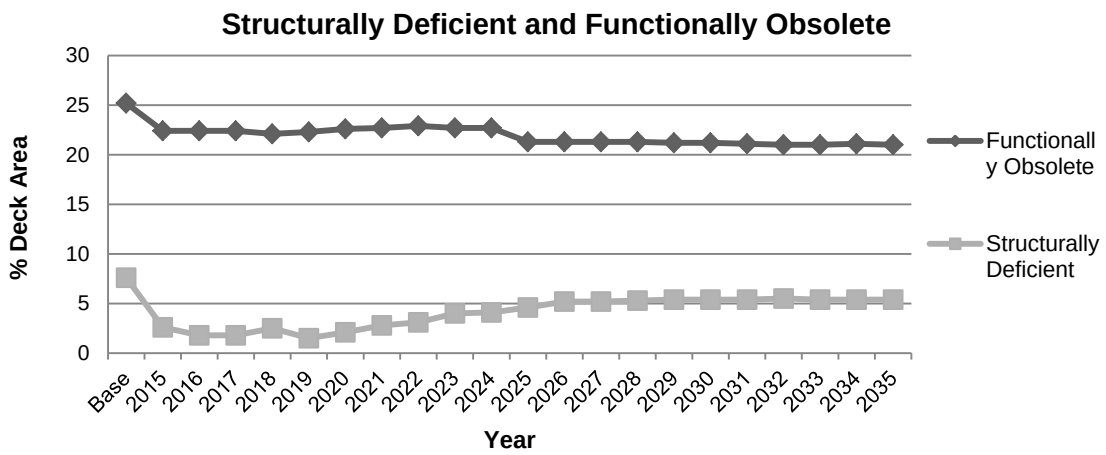


Figure D-16. Number of Structurally Deficient and Functionally Obsolete bridges (Scenario 1).

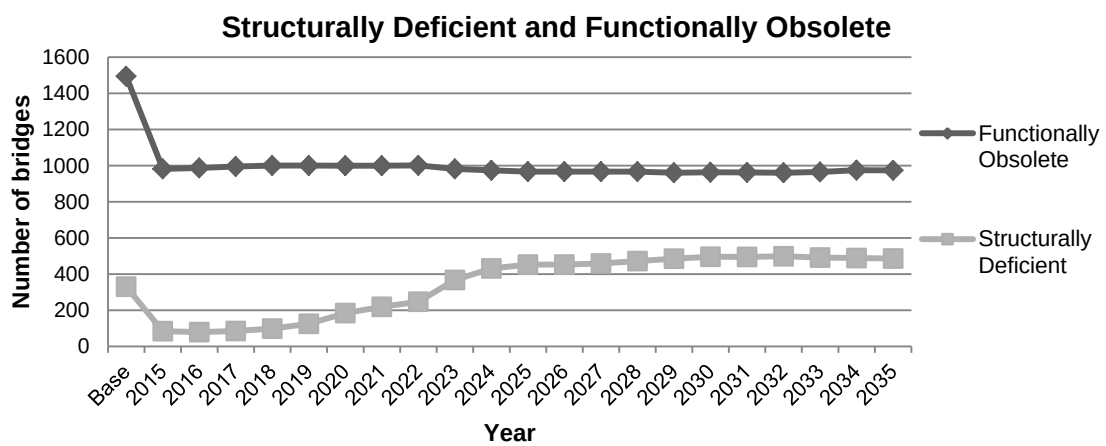


Figure D-17. Percentage Deck area of Structurally Deficient and Functionally Obsolete bridges (Scenario1).

In these figures the percentage classified as SD or FO drops once initial needs are met, then gradually increases to a steady-state value that reflects the percentage that become SD each year, and the bridges the system allows to remain in SD or FO condition.

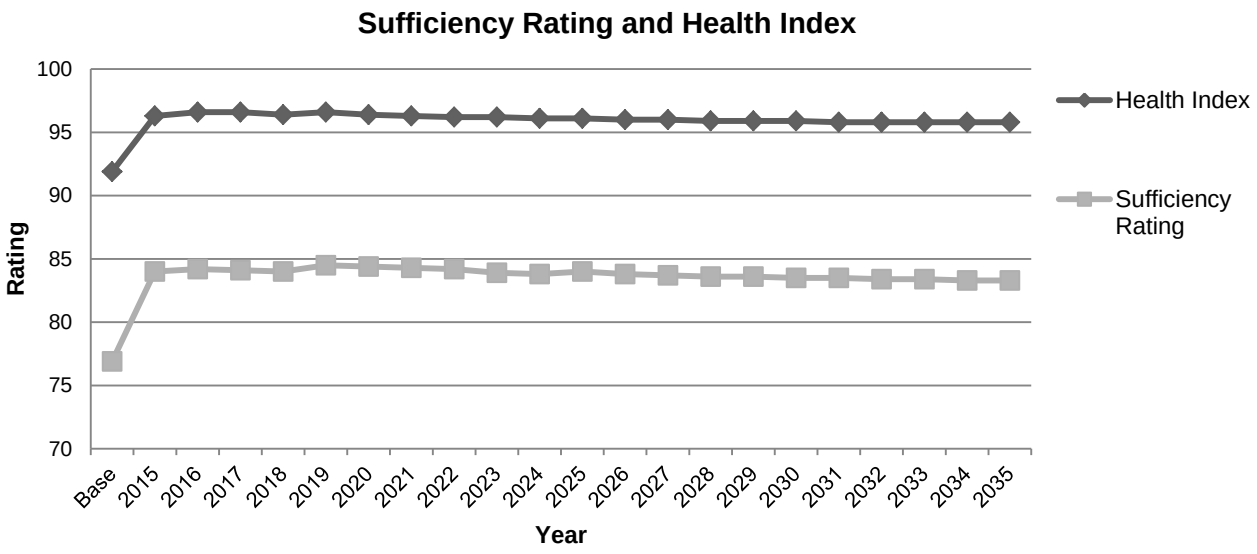
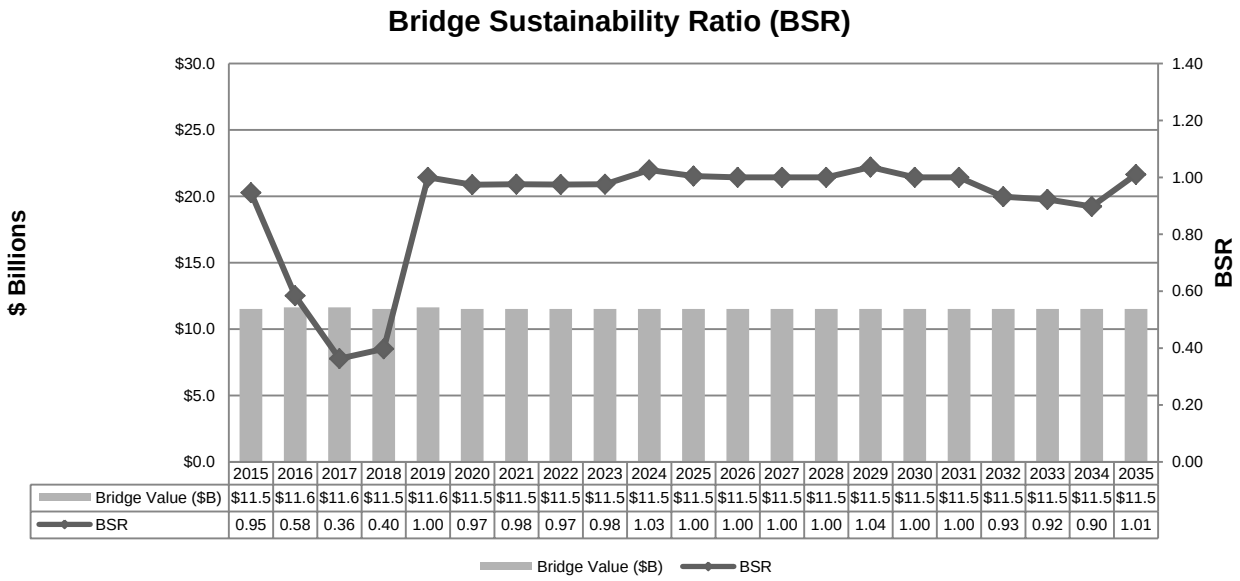


Figure D-18. Average Sufficiency Rating and Health Index over time (Scenario 1).



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bridge Value ($B)	$11.5	$11.6	$11.6	$11.5	$11.6	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5	$11.5
BSR	0.95	0.58	0.36	0.40	1.00	0.97	0.98	0.97	0.98	1.03	1.00	1.00	1.00	1.00	1.04	1.00	1.00	0.93	0.92	0.90	1.01

Figure D-19. Bridge Sustainability Ratio over time (Scenario 1).

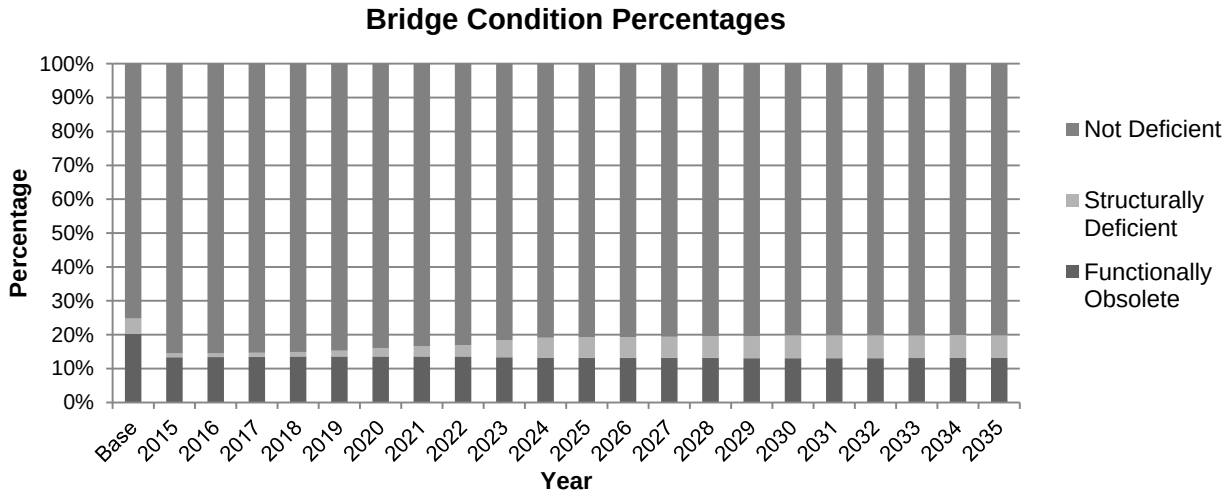


Figure D-20. Percentage of Structurally Deficient or Functionally Obsolete bridges (Scenario 1).

D.6.4 Scenario 3.a - 10-Year Deferral

In Scenario 3.a, work is deferred for 10 years. This scenario, compared with Scenario 1, quantifies the results of delaying maintenance. In this scenario, the backlog of remaining needs is $9,882 million as after 10 years. Tables D-20 to D-25 document the results of this scenario and Figures D-21 to D-28 present the results graphically.

Tables D-20 and D-21 show the total needs (TFND), total work (TWTD), backlog of needs (TFXD), MR&R needs (MRND), MR&R work done (MRWD), MR&R work offset by replacement (MRJD), MR&R backlog (MRXD), user benefits obtained (UBOD), obtained user benefits of MR&R (UOMD), health index (HIXA), and structurally deficient deck area (SDPC) under Scenario 3.a for each year of the analysis. In Table D-20, the values are not discounted and in Table D-21, the values are discounted at a rate of 7%. In this scenario the backlog of needs are $9,882 million after 10 years of deferred work and the $0 at the end of the analysis period.

Table D-20. Undiscounted MOEs by analysis year (Scenario 3.a).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3,160	0	3,160	179	0	0	179	0	0	90	8
2016	3,498	0	3,498	212	0	0	212	0	0	89	11
2017	4,085	0	4,085	236	0	0	236	0	0	87	15
2018	4,661	0	4,661	268	0	0	268	0	0	86	21
2019	5,401	0	5,401	300	0	0	300	0	0	84	30
2020	6,113	0	6,113	339	0	0	339	0	0	82	42
2021	6,896	0	6,896	377	0	0	377	0	0	81	55
2022	7,658	0	7,658	393	0	0	393	0	0	79	70
2023	8,920	0	8,920	372	0	0	372	0	0	78	82
2024	9,882	0	9,882	350	0	0	350	0	0	76	87
2025	10,818	10,702	196	325	322	3	0	2,055	16	98	91

Table D-20. Undiscounted MOEs by analysis year (Scenario 3.a). (Continued)

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2026	244	110	134	47	47	0	0	0	0	97	2
2027	182	48	134	48	48	0	0	0	0	97	2
2028	183	182	1	49	49	0	0	2	0	97	1
2029	53	52	1	50	50	0	0	3	3	97	0
2030	53	52	1	52	52	0	0	5	5	97	1
2031	56	55	0	55	55	0	0	5	5	97	1
2032	59	59	0	57	57	0	0	6	6	96	0
2033	59	58	0	58	58	0	0	6	6	96	1
2034	74	74	0	59	59	0	0	7	6	96	3
2035	60	60	0	59	59	0	0	6	6	96	4

Table D-21. Discounted MOEs by analysis year (Scenario 3.a).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3160	0	3160	179	0	0	179	0	0	90	8
2016	3269	0	3269	198	0	0	198	0	0	89	11
2017	3568	0	3568	206	0	0	206	0	0	87	15
2018	3805	0	3805	218	0	0	218	0	0	86	21
2019	4120	0	4120	229	0	0	229	0	0	84	30
2020	4359	0	4359	242	0	0	242	0	0	82	42
2021	4595	0	4595	251	0	0	251	0	0	81	55
2022	4769	0	4769	245	0	0	245	0	0	79	70
2023	5192	0	5192	216	0	0	216	0	0	78	82
2024	5375	0	5375	190	0	0	190	0	0	76	87
2025	5500	5441	100	165	163	2	0	1045	8	98	91
2026	116	52	64	22	22	0	0	0	0	97	2
2027	81	21	60	21	21	0	0	0	0	97	2
2028	76	76	0	20	20	0	0	1	0	97	1
2029	21	20	0	19	19	0	0	1	1	97	0
2030	19	19	0	19	19	0	0	2	2	97	1
2031	19	19	0	19	19	0	0	2	2	97	1
2032	19	19	0	18	18	0	0	2	2	96	0
2033	17	17	0	17	17	0	0	2	2	96	1
2034	21	20	0	16	16	0	0	2	2	96	3
2035	15	15	0	15	15	0	0	2	2	96	4

Tables D-22, D-23, and D-24 show the number of bridges by rating value for the deck, superstructure, and substructure respectively. The bridge appraisal rating varies from 9 (best condition) to 0 (worst condition). The tables show deterioration in condition ratings for these bridge components during the 10 years that work is being deferred and improves dramatically once work is restored. The tables show that even after work is restored, the system will allow some bridge components to exist in poor condition (rating of 4 or less).

Table D-22. Number of bridges by deck rating and analysis year (Scenario 3.a).

Deck Rating	9	8	7	6	5	4	3	2	1	0	N
Base	19	1256	3842	1672	384	91	62	4	0	0	29
2015	6	311	2454	3304	947	206	71	19	0	0	41
2016	2	84	1076	3850	1805	383	87	30	1	0	41
2017	0	20	477	2717	3183	716	157	45	3	0	41
2018	0	5	265	1596	3847	1261	271	68	5	0	41
2019	0	2	169	1057	3557	1911	508	106	8	0	41
2020	0	0	93	822	2532	2909	745	203	14	0	41
2021	0	0	24	686	1750	3500	1041	287	29	1	41
2022	0	0	7	513	1274	3718	1292	448	65	1	41
2023	0	0	3	277	1124	3338	1836	622	113	5	41
2024	0	0	0	186	1018	2569	2567	809	163	6	41
2025	4371	366	842	999	706	23	11	0	0	0	41
2026	1462	3857	452	570	956	10	11	0	0	0	41
2027	1029	2664	2133	511	964	6	11	0	0	0	41
2028	891	2258	2540	555	1060	8	6	0	0	0	41
2029	834	2032	2286	842	1304	15	5	0	0	0	41
2030	813	1823	2263	1053	1346	16	4	0	0	0	41
2031	815	1813	1999	1257	1416	17	1	0	0	0	41
2032	1395	1243	1919	1313	1396	51	1	0	0	0	41
2033	1520	1124	1900	1322	1343	109	1	0	0	0	41
2034	1526	1124	1670	1177	1711	109	0	1	0	0	41
2035	1523	1129	1669	766	2093	138	0	0	0	0	41

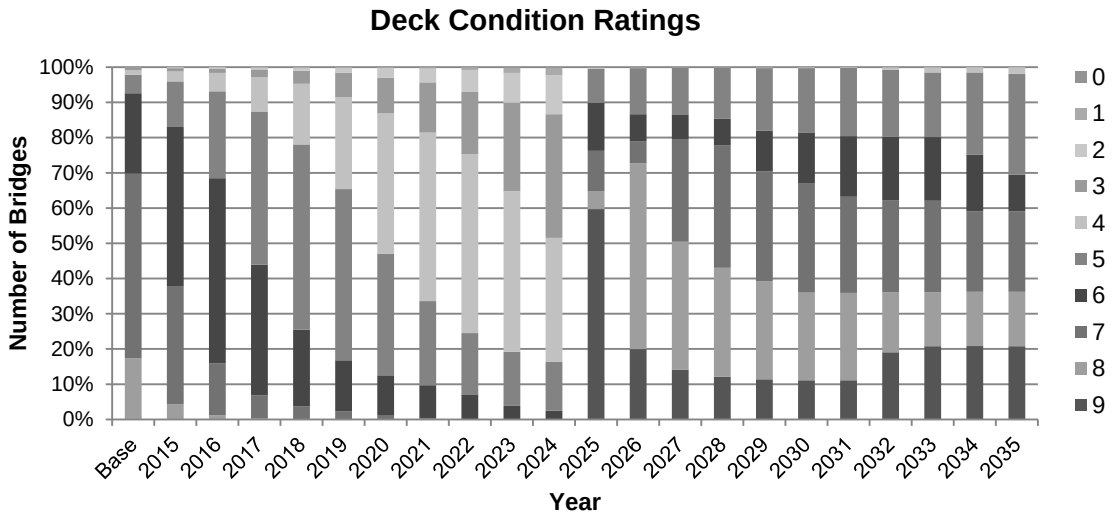


Figure D-21. Deck condition ratings over time (Scenario 3.a).

Table D-23. Number of bridges by superstructure rating and analysis year (Scenario 3.a).

Superstructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	20	1318	3682	1801	454	65	13	6	0	0	0
2015	8	620	2598	2938	957	207	24	7	0	0	0
2016	1	290	1741	3302	1608	355	54	7	1	0	0
2017	0	105	1099	3007	2375	664	95	11	3	0	0
2018	0	11	788	2551	2655	1139	189	21	5	0	0
2019	0	6	514	2193	2610	1601	383	46	6	0	0
2020	0	3	334	1915	2272	2133	209	82	11	0	0
2021	0	2	204	1486	2293	2238	938	179	19	0	0
2022	0	0	110	1107	2237	2306	1319	247	32	1	0
2023	0	0	28	879	2223	2038	1761	375	54	1	0
2024	0	0	15	645	2174	1685	2192	531	114	3	0
2025	4303	1928	887	173	57	4	3	4	0	0	0
2026	3834	3239	104	172	6	2	0	1	1	0	0
2027	3437	3411	323	184	0	2	0	1	1	0	0
2028	3402	3448	135	372	0	1	0	1	0	0	0
2029	3423	3175	384	191	184	1	0	1	0	0	0
2030	3394	3197	373	187	206	1	0	0	1	0	0
2031	3358	2957	642	208	205	1	1	0	0	0	0
2032	3345	2957	642	208	205	1	1	0	0	0	0
2033	3341	2952	650	209	22	184	1	0	0	0	0
2034	3341	2945	543	329	18	182	1	0	0	0	0
2035	3324	2942	562	331	18	182	0	0	0	0	0

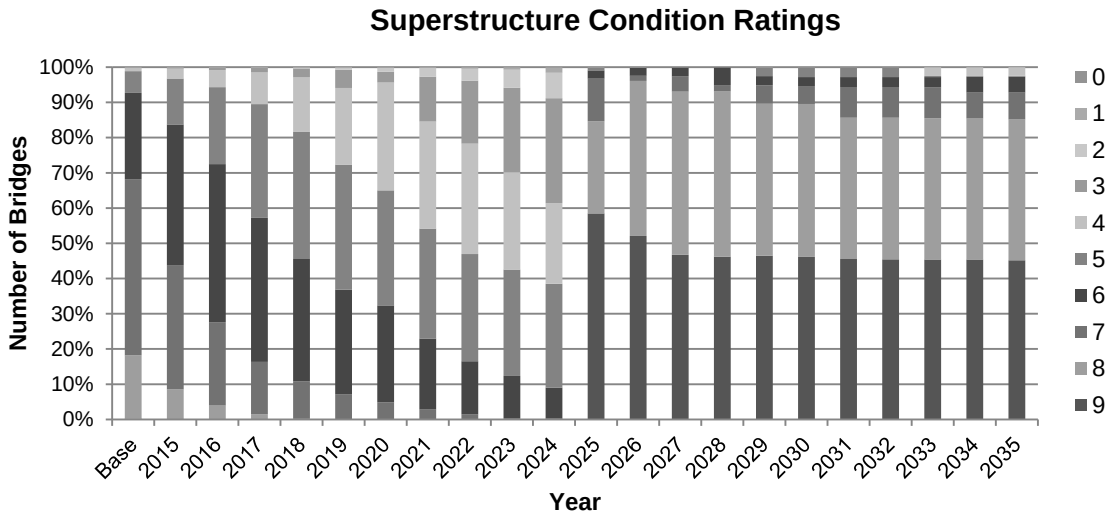


Figure D-22. Superstructure condition ratings over time (Scenario 3.a).

Table D-24. Number of bridges by substructure rating and analysis year (Scenario 3.a).

Substructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	18	1287	4011	1422	467	111	25	17	1	0	0
2015	12	660	3039	2556	779	201	39	17	3	0	53
2016	6	304	2267	3194	1159	299	55	13	8	1	53
2017	0	100	1546	3581	1534	439	80	15	10	1	53
2018	0	12	854	3848	1807	626	124	24	10	1	53
2019	0	9	571	3367	2195	942	179	31	11	1	53
2020	0	1	371	2704	2765	1141	270	41	12	1	53
2021	0	0	162	2118	3299	1213	446	54	13	1	53
2022	0	0	17	1528	3643	1250	760	90	17	1	53
2023	0	0	10	955	3713	1574	907	123	22	2	53
2024	0	0	3	647	3431	2071	920	206	24	4	53
2025	4267	2422	581	27	8	1	0	0	0	0	53
2026	6221	1056	1	26	2	0	0	0	0	0	53
2027	5696	1449	133	25	3	0	0	0	0	0	53
2028	5715	1387	46	157	1	0	0	0	0	0	53
2029	5732	1192	224	148	10	0	0	0	0	0	53
2030	5732	1174	242	8	150	0	0	0	0	0	53
2031	5732	1174	221	24	155	0	0	0	0	0	53
2032	5732	1174	146	96	158	0	0	0	0	0	53
2033	5732	1174	125	117	158	0	0	0	0	0	53
2034	5738	1128	148	134	48	110	0	0	0	0	53
2035	5739	1128	137	145	27	130	0	0	0	0	53

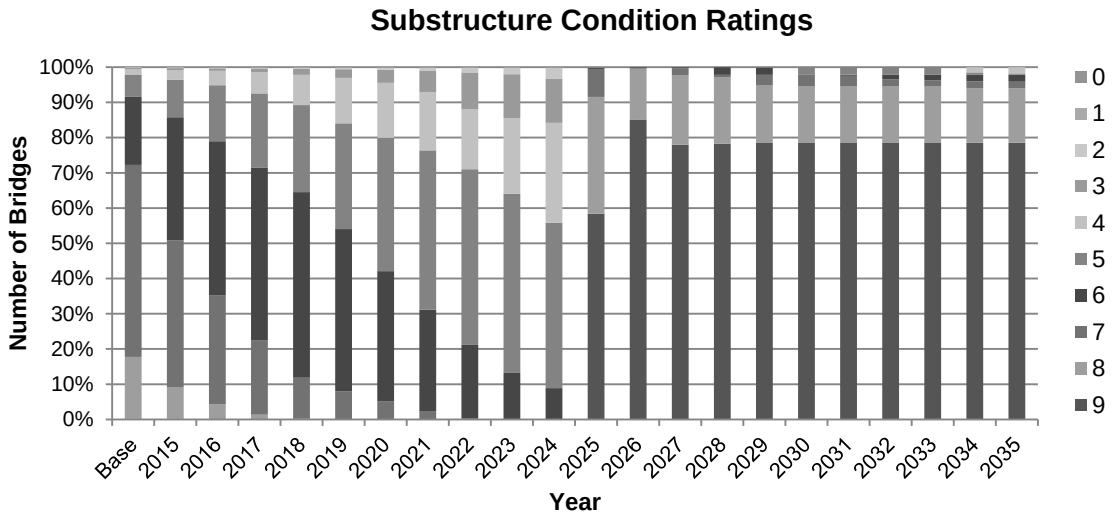


Figure D-23. Substructure condition ratings over time (Scenario 3.a).

Table D-25 shows predicted bridge conditions for Scenario 3.a, measures shown in the table include the number of bridges in good condition (SR > 80), the number of bridges in fair condition (SR between 50 and 80), and the number of bridges in poor condition (SR < 50), as well as number of SD and FO bridges, average SR, and average HI. Figures D-24 to D-28 present this information graphically. In interpreting the results it is important to note that following the end of the deferral period the budget is increased, and the system is allowed to perform all recommended work. This serves to demonstrate the investment required to restore conditions following the end of the deferral period. Particularly in comparison to Scenario 1, one can see that during the deferral period the needs steadily increase, and the end result of delaying work is that costs are higher, as in many cases bridge reconstruction or replacement is required as a result of delaying needed maintenance. Further, it is important to note that although all work is delayed during the 10-year deferral period, the escalation in needs is a result of delaying maintenance work as there is no increase in cost for delaying reconstruction or replacement work in NBIAS

Table D-25. Predicted bridge-level conditions by analysis year (Scenario 3.a).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2060	471	1824	32.8	330	7.6	1494	25.2	76.9	91.9
2015	4045	2674	640	2024	34.9	620	11.0	1404	23.9	74.8	90.3
2016	3732	2789	838	2229	36.7	949	14.8	1280	21.9	72.8	88.7
2017	3321	2923	1115	2607	40.5	1507	21.3	1100	19.1	70.2	87.2
2018	2893	3028	1438	3208	47.3	2286	30.5	922	16.8	67.4	85.6
2019	2490	3100	1769	3996	54.7	3259	42.0	737	12.7	64.3	84.0
2020	2006	3245	2108	5016	65.4	4475	55.0	541	10.3	61.1	82.4
2021	1589	3289	2481	5820	77.3	5437	70.0	383	7.3	57.9	80.8
2022	1237	3203	2919	6298	86.0	6022	81.7	276	4.3	54.3	79.3

Table D-25. Predicted bridge-level conditions by analysis year (Scenario 3.a). (Continued)

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
2023	1031	2922	3406	6564	90.3	6356	87.3	208	3.0	51.2	77.7
2024	870	2568	3921	6687	92.9	6534	90.7	153	2.3	48.2	76.1
2025	6606	741	12	751	16.1	47	1.8	704	14.3	88.6	97.8
2026	6636	719	4	732	15.7	31	1.5	701	14.2	88.6	97.5
2027	6624	731	4	730	15.6	26	0.9	704	14.8	88.5	97.2
2028	6622	735	2	730	15.1	23	0.4	707	14.8	88.7	97.1
2029	6512	845	2	735	15.2	29	0.5	706	14.7	88.4	96.9
2030	6426	931	2	736	15.2	29	0.5	707	14.7	88.3	96.7
2031	6413	945	1	735	15.1	27	0.5	708	14.7	88.2	96.5
2032	6402	956	1	768	15.8	62	1.2	706	14.6	88.1	96.4
2033	6319	1033	7	979	17.7	302	3.4	677	14.3	87.8	96.3
2034	6238	1119	2	1076	17.9	410	3.6	666	14.3	87.7	96.3
2035	6217	1139	3	1118	18.6	458	4.7	660	13.8	87.5	96.2

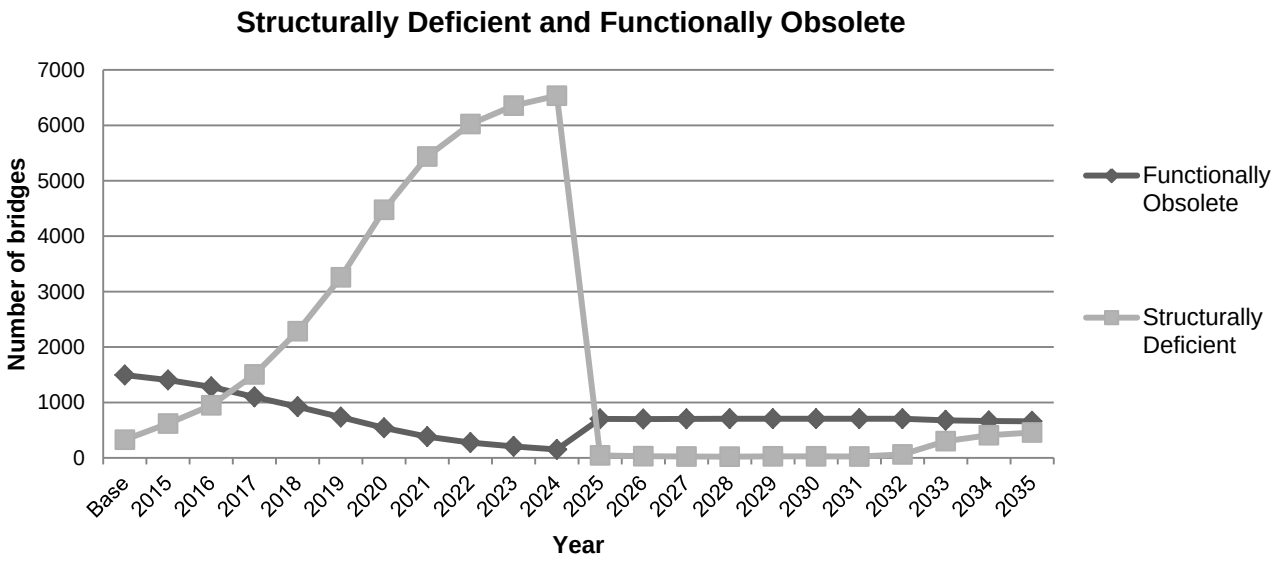


Figure D-24. Number of structurally deficient and functionally obsolete bridges (Scenario 3.a).

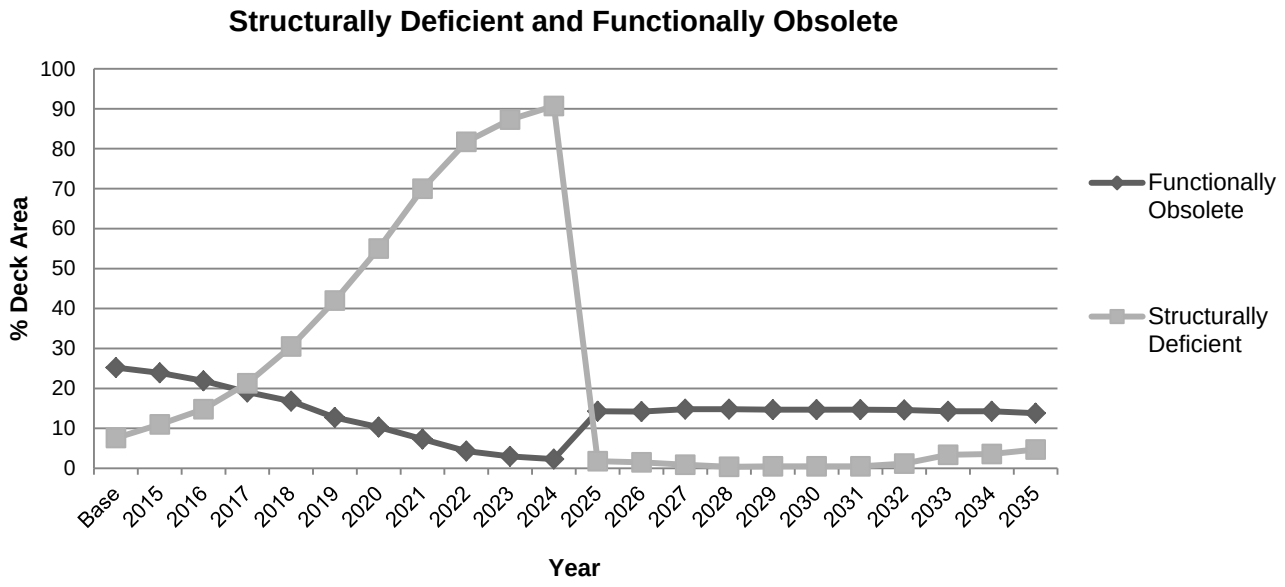


Figure D-25. Percent deck area of structurally deficient and functionally obsolete bridges (Scenario 3.a).

In reviewing the above figures, it is important to note that a bridge that is both SD and FO is classified as SD; hence the decline in FO bridges even during the deferral period as they transition to becoming SD. At the end of the deferral period, the number of SD bridges drops as unmet needs are addressed.

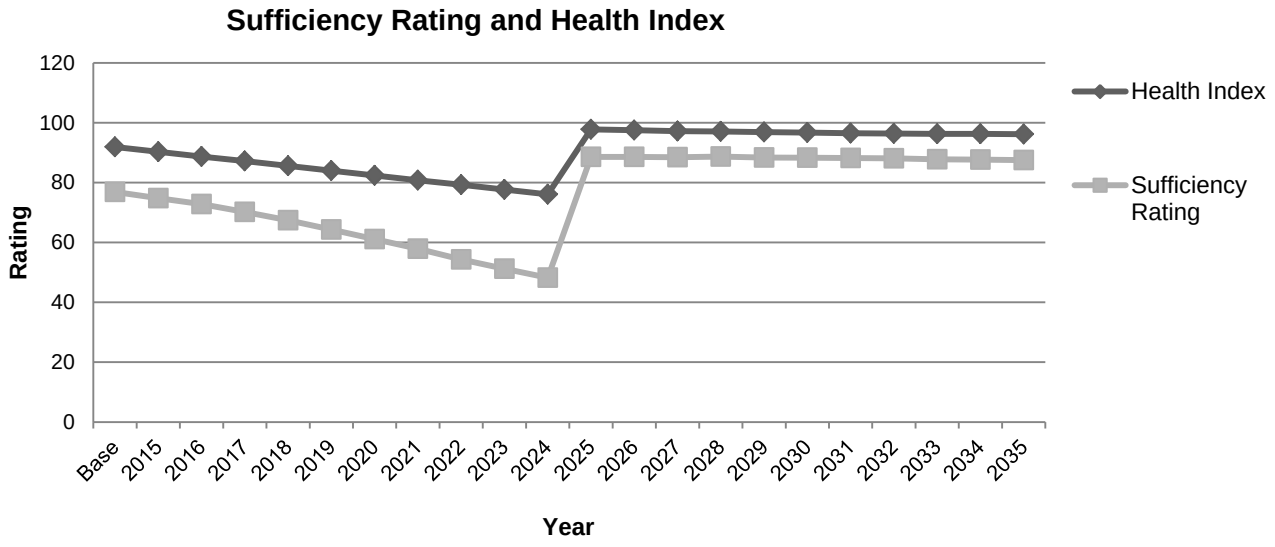
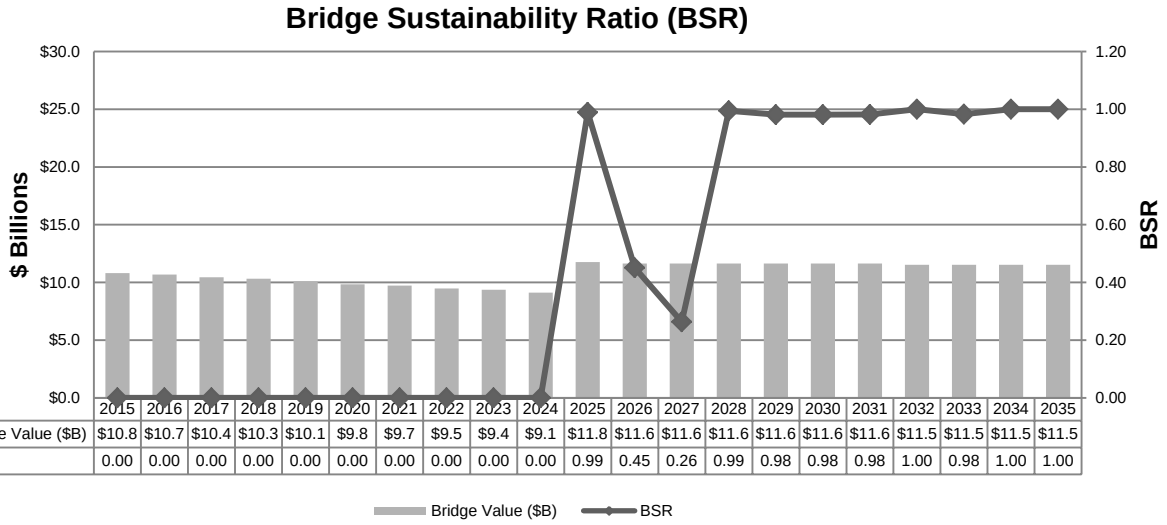


Figure D-26. Average sufficiency rating and Health Index over time (Scenario 3.a).



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Bridge Value ($B)	$10.8	$10.7	$10.4	$10.3	$10.1	$9.8	$9.7	$9.5	$9.4	$9.1	$11.8	$11.6	$11.6	$11.6	$11.6	$11.6	$11.6	$11.5	$11.5	$11.5	$11.5
BSR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.45	0.26	0.99	0.98	0.98	0.98	1.00	0.98	1.00	1.00

Figure D-27. Bridge sustainability ratio over time (Scenario 3.a).

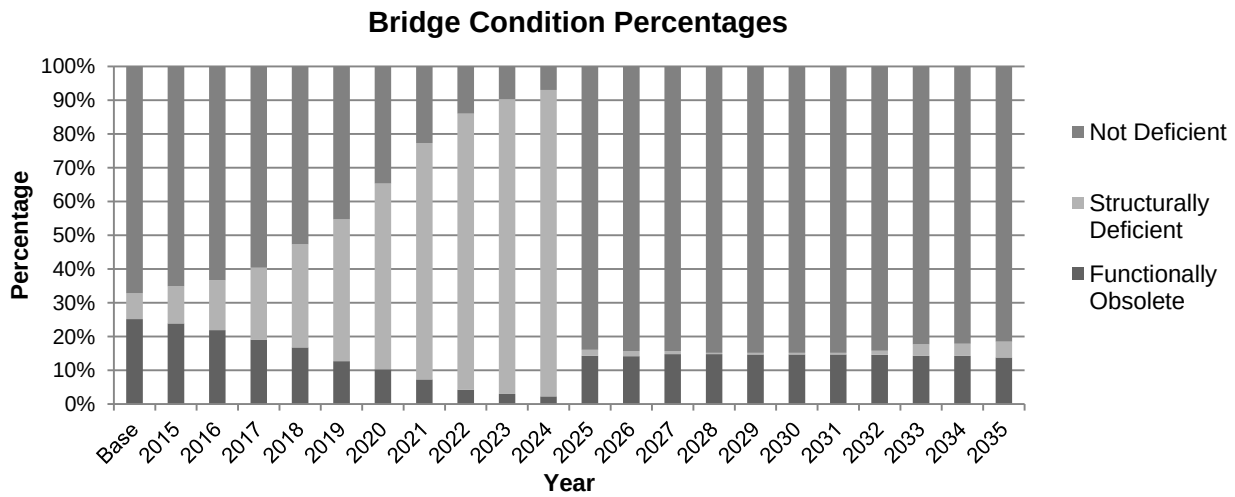


Figure D-28. Percentage structurally deficient or functionally obsolete bridges (Scenario 3.a).

D.6.5 Scenario 3.b - 20-Year Deferral

In Scenario 3.b, work is deferred for 20 years. This scenario, compared with Scenario 1, quantifies the results of deferring work for 20 years. In this scenario, the backlog of remaining needs is $17,257 million after 20 years. Tables D-26 to D-31 document the results of this scenario and Figures D-29 to D-31 show the results graphically.

Tables D-26 and D-27 show the total needs (TFND), total work (TWTD), backlog of needs (TFXD), MR&R needs (MRND), MR&R work done (MRWD), MR&R work offset by replacement (MRJD), MR&R backlog (MRXD), user benefits obtained (UBOD), obtained user benefits of MR&R (UOMD), health index (HIXA), and structurally deficient deck area (SDPC) under Scenario 3.b for each year of the analysis. In Table D-26, the values are not discounted; and in Table D-27, the values are discounted at a rate of 7%. In this scenario the backlog of needs are $17,257 million after 20 years of deferred work.

Table D-26. Undiscounted MOEs by analysis year (Scenario 3.b).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3160	0	3160	179	0	0	179	0	0	90	8
2016	3498	0	3498	212	0	0	212	0	0	89	11
2017	4085	0	4085	236	0	0	236	0	0	87	15
2018	4661	0	4661	268	0	0	268	0	0	86	21
2019	5401	0	5401	300	0	0	300	0	0	84	30
2020	6113	0	6113	339	0	0	339	0	0	82	42
2021	6896	0	6896	377	0	0	377	0	0	81	55
2022	7658	0	7658	393	0	0	393	0	0	79	70
2023	8920	0	8920	372	0	0	372	0	0	76	87
2024	9882	0	9882	350	0	0	350	0	0	76	87
2025	10818	0	10818	325	0	0	325	0	0	75	91
2026	11619	0	11619	304	0	0	304	0	0	73	92
2027	12418	0	12418	276	0	0	276	0	0	72	94
2028	13425	0	13425	220	0	0	220	0	0	70	96
2029	14431	0	14431	172	0	0	172	0	0	69	98
2030	15111	0	15111	145	0	0	145	0	0	67	99
2031	15785	0	15785	112	0	0	112	0	0	66	99
2032	16435	0	16435	79	0	0	79	0	0	64	100
2033	16908	0	16908	54	0	0	54	0	0	63	100
2034	17257	0	17257	37	0	0	37	0	0	62	100
2035	17429	17436	0	30	30	0	0	2603	1	100	100

Table D-27. Discounted MOEs by analysis year (Scenario 3.b).

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2015	3160	0	3160	179	0	0	179	0	0	90	8
2016	3269	0	3269	198	0	0	198	0	0	89	11
2017	3568	0	3568	206	0	0	206	0	0	87	15
2018	3805	0	3805	218	0	0	218	0	0	86	21
2019	4120	0	4120	229	0	0	229	0	0	84	30
2020	4359	0	4359	242	0	0	242	0	0	82	42
2021	4595	0	4595	251	0	0	251	0	0	81	55
2022	4769	0	4769	245	0	0	245	0	0	79	70
2023	5192	0	5192	216	0	0	216	0	0	78	82
2024	5375	0	5375	190	0	0	190	0	0	76	87
2025	5500	0	5500	165	0	0	165	0	0	75	91
2026	5520	0	5520	144	0	0	144	0	0	73	92

Table D-27. Discounted MOEs by analysis year (Scenario 3.b). (Continued)

Year	TFND ($M)	TWTD ($M)	TFXD ($M)	MRND ($M)	MRWD ($M)	MRJD ($M)	MRXD ($M)	UBOD ($M)	UOMD ($M)	HIXA (%)	SDPC (%)
2027	5514	0	5514	122	0	0	122	0	0	72	94
2028	5571	0	5571	91	0	0	91	0	0	70	96
2029	5596	0	5596	67	0	0	67	0	0	69	98
2030	5477	0	5477	52	0	0	52	0	0	67	99
2031	5347	0	5347	38	0	0	37	0	0	66	99
2032	5203	0	5203	25	0	0	25	0	0	64	100
2033	5002	0	5002	16	0	0	16	0	0	63	100
2034	4772	0	4772	10	0	0	10	0	0	62	100
2035	4504	4506	0	8	8	0	0	673	0	100	100

Tables D-28, D-29, and D-30 show the number of bridges by rating value for the deck, superstructure, and substructure respectively. The bridge appraisal rating varies from 9 (best condition) to 0 (worst condition). The tables show deterioration in condition ratings for these bridge components during the 20 years that work is being deferred and improves dramatically once work is restored. The tables show that even after work is restored, the tables show that even with an unconstrained budget after the 20-year deferral, the system will allow some bridge components to exist in poor condition (rating of 4 or less).

Table D-28. Number of bridges by deck rating and analysis year (Scenario 3.b).

Deck Rating	9	8	7	6	5	4	3	2	1	0	N
Base	19	1256	3842	1672	384	91	62	4	0	0	29
2015	6	311	2454	3304	947	206	71	19	0	0	41
2016	2	84	1076	3850	1805	383	87	30	1	0	41
2017	0	20	477	2717	3183	716	157	45	3	0	41
2018	0	5	265	1596	3847	1261	271	68	5	0	41
2019	0	2	169	1057	3557	1911	508	106	8	0	41
2020	0	0	93	822	2532	2909	745	203	14	0	41
2021	0	0	24	686	1750	3500	1041	287	29	1	41
2022	0	0	7	513	1274	3718	1292	448	65	1	41
2023	0	0	3	277	1124	3338	1836	622	113	5	41
2024	0	0	0	186	1018	2569	2567	809	163	6	41
2025	0	0	0	120	951	1825	3176	992	239	15	41
2026	0	0	0	51	895	1343	3466	1159	366	38	41
2027	0	0	0	14	754	1022	3805	1154	510	59	41
2028	0	0	0	7	602	1037	3641	1283	670	78	41
2029	0	0	0	0	430	1069	3181	1724	827	87	41
2030	0	0	0	0	255	1149	2585	2212	1013	104	41
2031	0	0	0	0	163	1093	2262	2502	1169	129	41

Table D-28. Number of bridges by deck rating and analysis year (Scenario 3.b). (Continued)

Deck Rating	9	8	7	6	5	4	3	2	1	0	N
2032	0	0	0	0	96	1054	1884	2845	1265	174	41
2033	0	0	0	0	41	1005	1346	3389	1289	248	41
2034	0	0	0	0	16	934	944	3775	1269	380	41
2035	7088	4	116	73	36	0	0	1	0	0	41

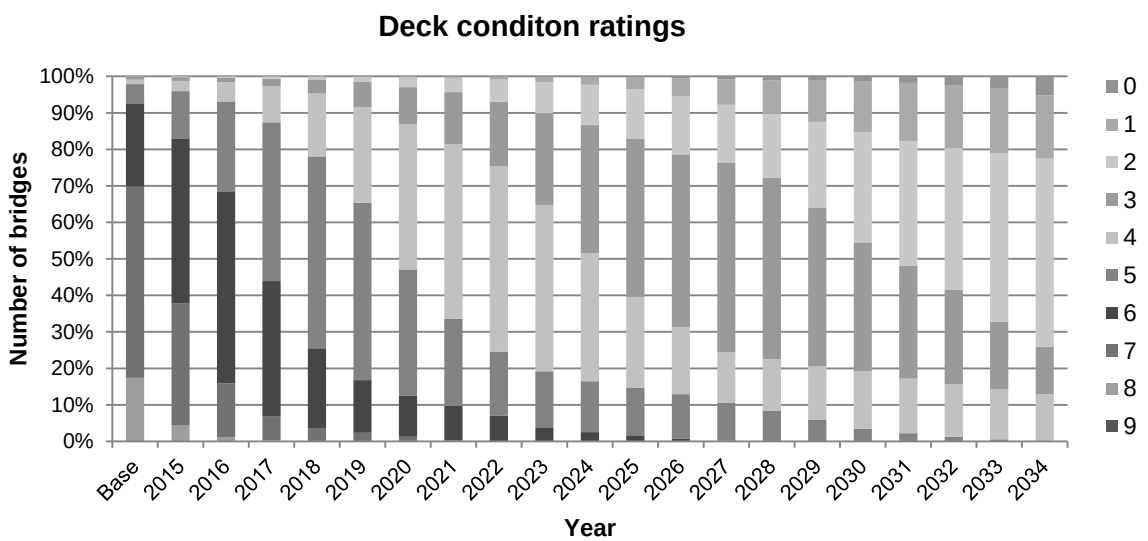


Figure D-29. Deck condition ratings over time (Scenario 3.b).

Table D-29. Number of bridges by superstructure rating and analysis year (Scenario 3.b).

Superstructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	20	1318	3682	1801	454	65	13	6	0	0	0
2015	8	620	2598	2938	957	207	24	7	0	0	0
2016	1	290	1741	3302	1608	355	54	7	1	0	0
2017	0	105	1099	3007	2375	664	95	11	3	0	0
2018	0	11	788	2551	2655	1139	189	21	5	0	0
2019	0	6	514	2193	2610	1601	393	46	6	0	0
2020	0	3	334	1915	2272	2133	609	82	11	0	0
2021	0	2	204	1486	2293	2238	938	179	19	0	0
2022	0	0	110	1108	2237	2306	1319	247	32	1	0
2023	0	0	28	879	2223	2038	1761	375	54	1	0
2024	0	0	15	645	2174	1685	2192	531	114	3	0
2025	0	0	10	421	2094	1623	2255	780	169	7	0
2026	0	0	9	309	1879	1670	2189	1091	196	16	0

Table D-29. Number of bridges by superstructure rating and analysis year (Scenario 3.b). (Continued)

Superstructure Rating	9	8	7	6	5	4	3	2	1	0	N
2027	0	0	8	206	1667	1796	2082	1362	219	29	0
2028	0	0	6	114	1415	1943	1756	1785	303	37	0
2029	0	0	6	50	1096	2159	1384	2163	447	54	0
2030	0	0	6	22	882	2203	1232	2346	557	113	0
2031	0	0	4	19	695	2194	1203	2385	716	146	0
2032	0	0	3	18	475	2202	1271	2406	823	161	0
2033	0	0	2	17	331	2143	1314	2351	1026	175	0
2034	0	0	0	16	250	2025	1374	2211	1296	187	0
2035	7072	178	101	6	2	0	0	0	0	0	0

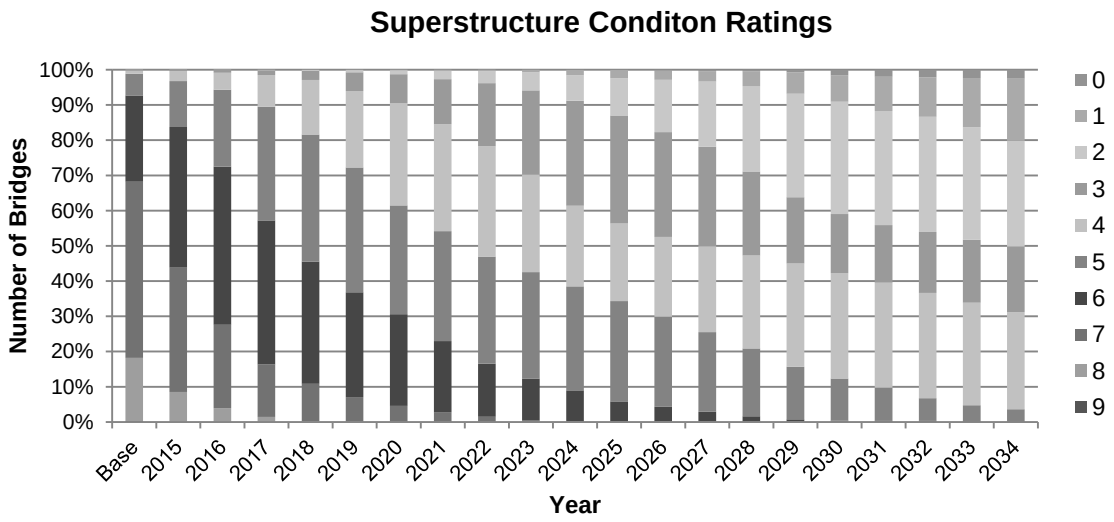


Figure D-30. Superstructure condition ratings over time (Scenario 3.b).

Table D-30. Number of bridges by substructure rating and analysis year (Scenario 3.b).

Substructure Rating	9	8	7	6	5	4	3	2	1	0	N
Base	18	1287	4011	1422	467	111	25	17	1	0	0
2015	12	660	3039	2556	779	201	39	17	3	0	53
2016	6	304	2267	3194	1159	299	55	13	8	1	53
2017	0	100	1546	3581	1534	439	80	15	10	1	53
2018	0	12	854	3848	1807	626	124	24	10	1	53
2019	0	9	571	3367	2195	942	179	31	11	1	53
2020	0	1	371	2704	2765	1141	270	41	12	1	53
2021	0	0	162	2118	3299	1213	446	54	13	1	53
2022	0	0	17	1528	3643	1250	760	90	17	1	53

Table D-30. Number of bridges by substructure rating and analysis year (Scenario 3.b). (Continued)

Substructure Rating	9	8	7	6	5	4	3	2	1	0	N
2023	0	0	10	955	3717	1574	907	123	22	2	53
2024	0	0	3	647	3431	2071	920	206	24	4	53
2025	0	0	0	429	3185	2440	882	340	26	4	53
2026	0	0	0	240	2914	2743	762	606	37	4	53
2027	0	0	0	75	2351	3275	769	784	48	4	53
2028	0	0	0	13	1830	3573	995	816	74	5	53
2029	0	0	0	6	1338	3706	1315	830	104	7	53
2030	0	0	0	1	893	3645	1786	800	172	9	53
2031	0	0	0	0	591	3518	2167	775	244	13	53
2032	0	0	0	0	381	3409	2414	635	454	13	53
2033	0	0	0	0	214	3182	2677	541	665	17	53
2034	0	0	0	0	55	3068	2831	564	768	20	53
2035	7022	4	280	0	0	0	0	0	0	0	53

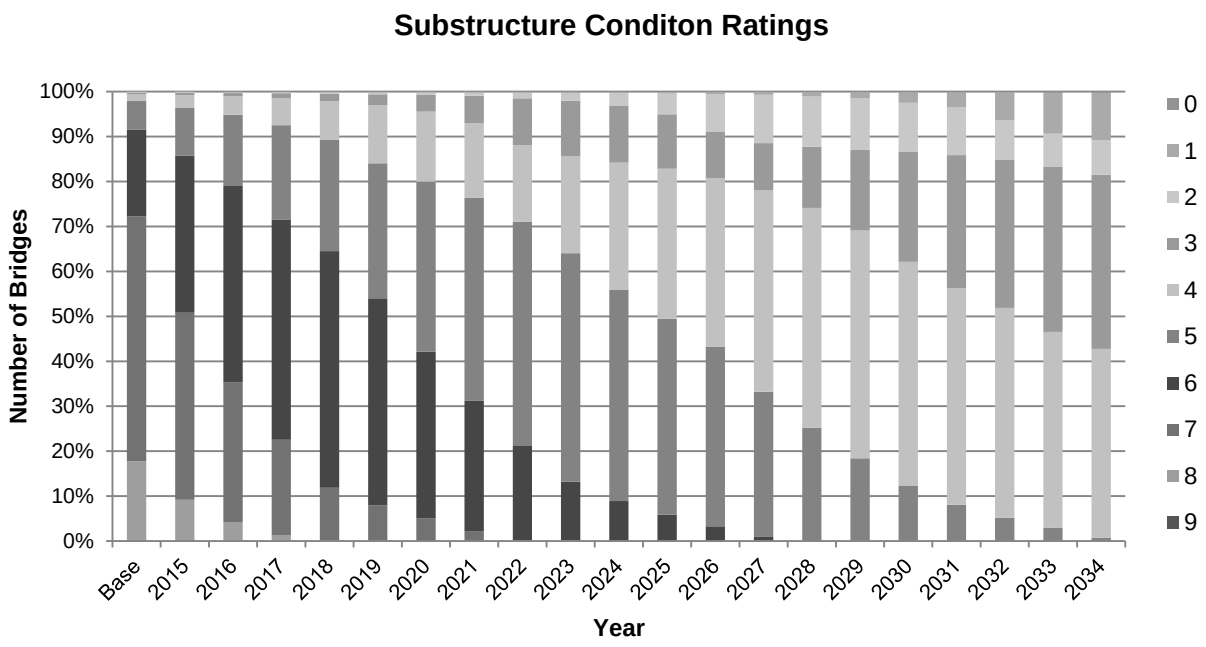


Figure D-31. Substructure condition ratings over time (Scenario 3.b).

Table D-31 shows predicted bridge conditions for Scenario 3.b. Measures shown in the table include the number of bridges in good condition (SR > 80), the number of bridges in fair condition (SR between 50 and 80), and the number of bridges in poor condition (SR < 50), as well as number of SD and FO bridges, average SR, and average HI. Figures D-32 to D-36 present this information graphically. In interpreting the results it is important to note that, as in the case of Scenario 3.a, following the end of the deferral period the budget is increased, and the system is allowed to perform all recommended work. This serves to demonstrate the investment required to restore conditions following the end of the deferral period. Particularly in comparison to Scenario 1, one can see that during the deferral period the needs steadily increase, and the end result of delaying work is that costs are higher, as in many cases bridge reconstruction or replacement is required as a result of delaying needed maintenance. Further, it is important to note that although all work is delayed during the 20-year deferral period, the escalation in needs is a result of delaying maintenance work, as there is no increase in cost for delaying reconstruction/replacement work in NBIAS. However, this can be an issue when using a 20-year deferral, as over this long a period a bridge may transition from needing maintenance work, to needing reconstruction/replacement, and ultimately to requiring closure as needs continue to be deferred.

Table D-31. Predicted bridge-level conditions by analysis year (Scenario 3.b).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.2	76.9	91.9
2015	4045	2674	640	2024	34.9	620	11.0	1404	23.9	74.8	90.3
2016	3732	2789	838	2229	36.7	949	14.8	1280	21.9	72.8	88.8
2017	3321	2923	1115	2607	40.5	1507	21.3	1100	19.1	70.2	87.2
2018	2893	3028	1438	3208	47.3	2296	30.5	922	16.8	67.4	85.6
2019	2490	3100	1769	3996	54.7	3259	42.0	737	12.7	64.3	84.0
2020	2006	3245	2108	5016	65.4	4475.	55.0	541	10.3	61.1	82.4
2021	1589	3289	2481	5820	77.3	5437	70.0	383	7.3	57.9	80.8
2022	1237	3203	2919	6298	86.0	6022	81.7	276	4.3	54.3	79.3
2023	1031	2922	3406	6564	90.3	6356	87.3	208	3.0	51.2	77.7
2024	870	2568	3921	6687	92.9	6534	90.7	153	2.7	48.2	76.1
2025	699	2406	4254	6788	94.0	6665	92.2	123	1.8	45.8	74.6
2026	551	2277	4531	6891	95.3	6799	93.8	92	1.5	43.3	73.1
2027	404	2171	4784	7026	96.9	6959	95.9	67	1.0	40.8	71.6
2028	322	2022	5015	7123	98.1	7081	97.6	42	0.5	38.7	70.1
2029	234	1914	5211	7205	99.0	7181	98.8	24	0.2	36.8	68.7
2030	187	1747	5425	7256	99.5	7246	99.4	10	0.1	34.9	67.2
2031	133	1626	5600	7291	99.7	7285	99.6	6	0.04	33.5	65.8
2032	84	1535	5740	7321	99.8	7319	99.8	2	0.01	31.8	64.4
2033	43	1440	5876	7334	99.9	7334	99.9	0	0	30.5	63.0
2034	8	1354	5997	7340	99.9	7340	99.9	0	0	29.2	61.7
2035	6948	411	0	566	11.9	10	0.1	556	11.8	90.0	99.9

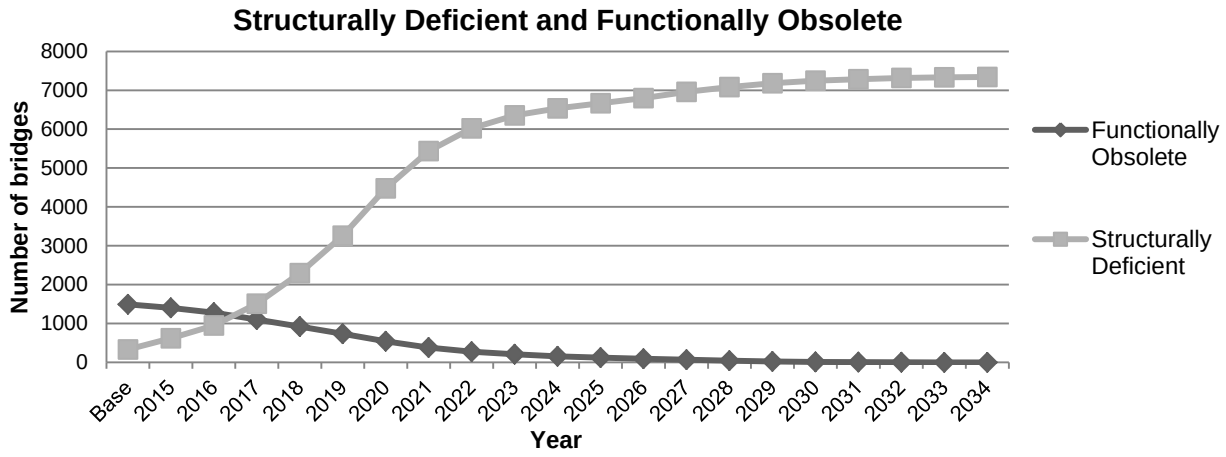


Figure D-32. Number of Structurally Deficient and Functionally Obsolete bridges over time (Scenario 3.b).

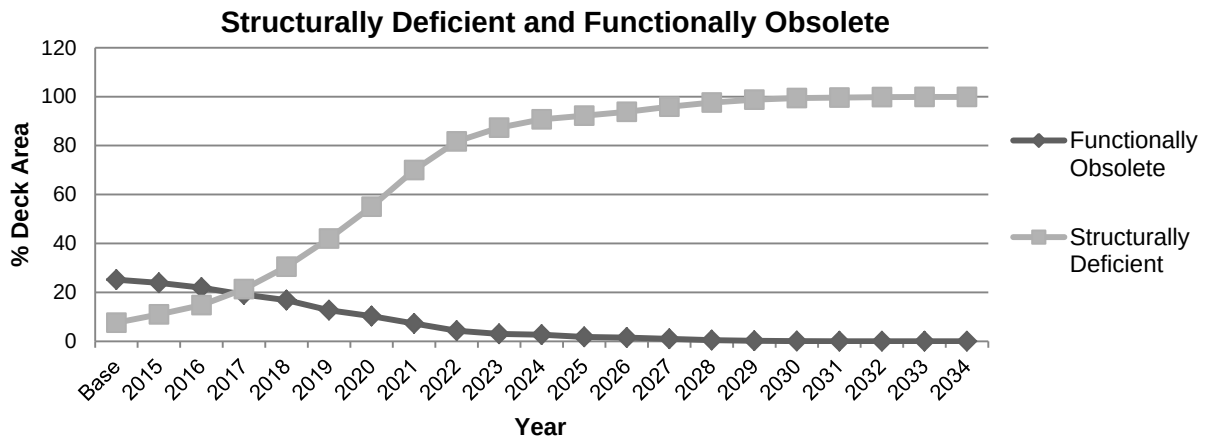


Figure D-33. Percent deck area of structurally deficient and functionally obsolete bridges over time (Scenario 3.b).

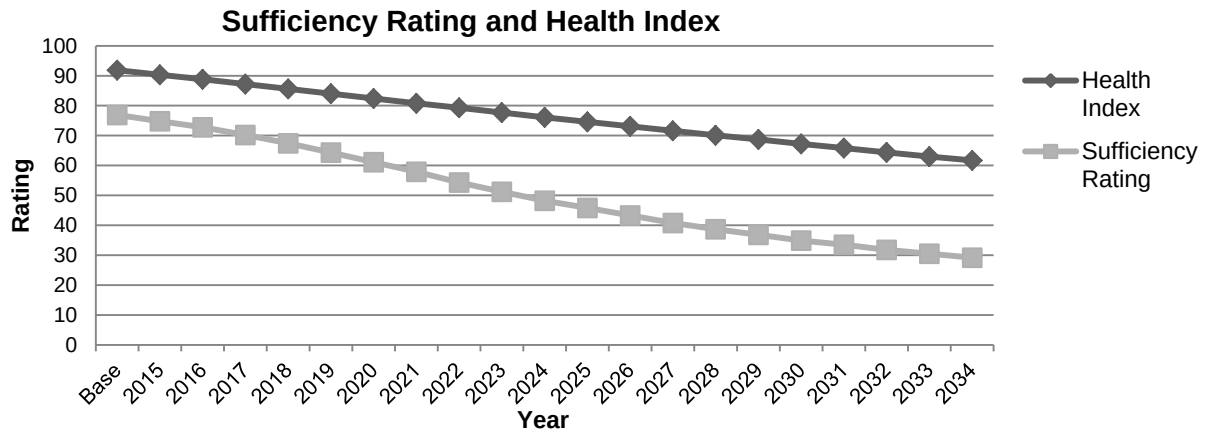
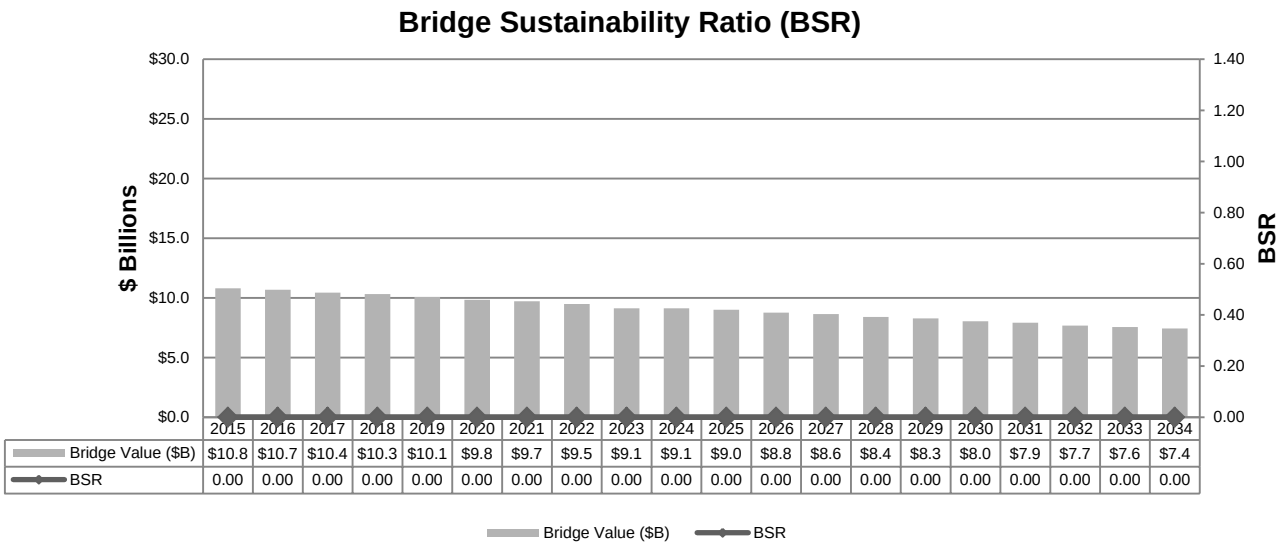


Figure D-34. Average sufficiency rating and Health Index over time (Scenario 3.b).



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Bridge Value ($B)	$10.8	$10.7	$10.4	$10.3	$10.1	$9.8	$9.7	$9.5	$9.1	$9.1	$9.0	$8.8	$8.6	$8.4	$8.3	$8.0	$7.9	$7.7	$7.6	$7.4
BSR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure D-35. Bridge sustainability ratio over time (Scenario 3.b).

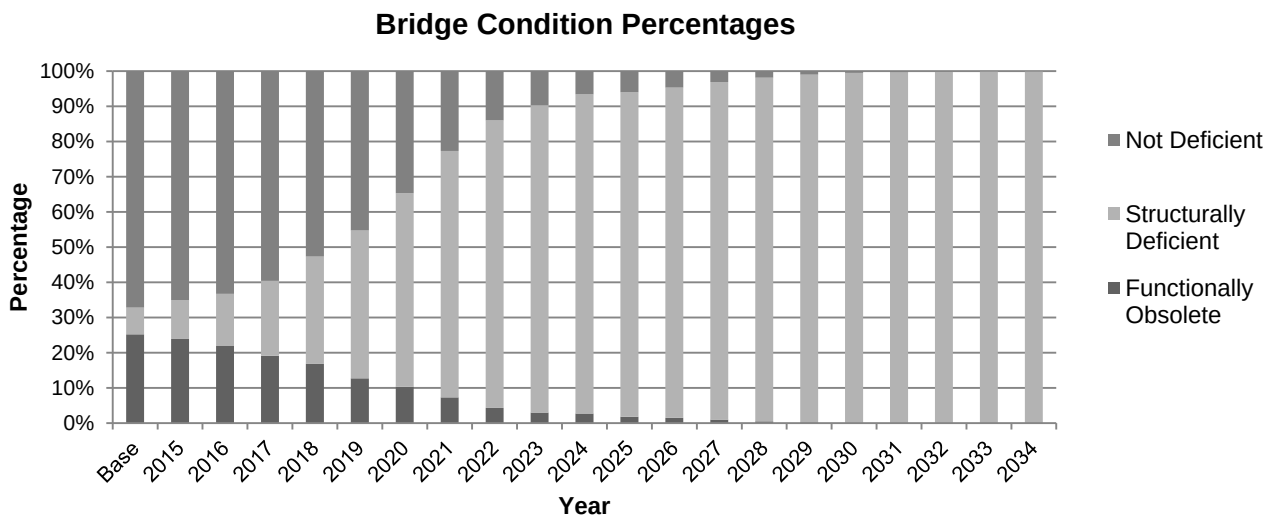


Figure D-36. Percentage of bridges identified as structurally deficient or functionally obsolete (Scenario 3.b).

D.6.6 Summary of Other Scenarios Analyzed

As noted above, comparing Scenario 3 to Scenario 1 provides a basic analysis of the impact of delaying maintenance over a 10-year or 20-year period. The other scenarios listed in Table D-12 provide additional insights on impacts of delay using more nuanced definitions of what gets delay and how this delay occurs. These can also be compared to Scenario 1 to help determine the effects of delaying maintenance. Tables D-32 through D-37 show the bridge condition results of the other scenarios. Figures D-37 through D-43 present the structurally deficient and functionally obsolete data graphically. Figure D-44 shows the number of bridges in good, fair, and poor condition; the sufficiency rating, and the health index for all the scenarios in year 2034.

Table D-32. Predicted bridge-level conditions by analysis year (Scenario 2).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.1	76.9	91.9
2015	5360	1869	140	1250	28.0	300	7.0	950	20.9	80.1	92.7
2016	5180	2025	154	1327	28.9	428	9.0	899	19.8	79.2	91.8
2017	4962	2193	204	1525	30.4	666	11.8	859	18.6	78.3	91.0
2018	4674	2455	230	1796	31.6	991	14.3	805	17.2	78.1	90.5
2019	4327	2767	265	2275	35.0	1520	18.5	755	16.5	76.9	89.8
2020	4036	3037	286	3049	40.6	2371	24.8	678	15.8	76.3	89.4
2021	3829	3197	333	3784	48.2	3209	35.3	575	12.9	75.1	88.7
2022	3622	3322	415	4284	55.1	3786	43.7	498	11.5	74.4	88.4
2023	3453	3410	496	4631	59.7	4174	48.7	457	10.9	73.7	87.9
2024	3279	3556	524	4843	60.1	4412	49.5	431	10.6	73.3	87.6
2025	3102	3683	574	4957	61.1	4546	50.8	411	10.4	72.7	87.2
2026	2936	3725	698	5045	61.7	4659	51.5	396	10.2	71.7	86.8
2027	2849	3775	735	5049	61.4	4670	51.3	379	10.1	71.3	86.6
2028	2751	3898	710	5068	61.1	4686	51.3	382	9.8	71.0	86.5
2029	2582	4050	727	5172	61.4	4808	51.8	364	9.5	70.6	86.3
2030	2421	4205	733	5241	61.9	4885	52.5	356	9.4	70.0	85.9
2031	2288	4312	759	5320	62.9	4983	54.0	337	8.9	69.4	85.7
2032	2219	4384	756	5382	63.3	5054	54.9	328	8.4	69.3	85.6
2033	2114	4498	747	5416	64.6	5093	56.3	323	8.3	68.7	85.4
2034	2007	4599	753	5470	65.7	5166	57.4	304	8.3	68.8	85.6
2035	1931	4654	774	5496	66.2	51.97	57.9	299	8.3	68.4	85.4

Table D-33. Predicted bridge-level conditions by analysis year (Scenario 3.c).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.2	76.9	91.9
2015	5756	1592	11	1074	25.1	93	2.7	981	22.4	83.9	95.7
2016	5733	1621	5	1073	24.2	86	1.8	987	22.4	84.1	95.7
2017	5708	1638	13	1091	24.2	100	2.4	991	21.8	83.9	95.6
2018	5688	1657	14	1109	23.4	116	1.4	993	22.0	84.5	95.6
2019	5571	1771	17	1166	24.0	184	1.9	982	22.2	84.4	95.4
2020	5543	1803	13	1234	24.4	248	2.9	986	21.5	84.5	95.4
2021	5519	1833	7	1257	24.8	270	3.3	987	21.5	84.4	95.2
2022	5419	1929	11	1391	25.9	425	4.3	969	21.6	84.1	95.1

Table D-33. Predicted bridge-level conditions by analysis year (Scenario 3.c). (Continued)

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
2023	5360	1995	4	1433	26.0	467	4.5	966	21.5	84.0	95.0
2024	5336	2019	4	1442	26.7	477	5.6	965	21.1	83.8	94.9
2025	5300	2055	4	1443	26.7	484	5.9	959	21.0	83.8	94.9
2026	5270	2085	4	1453	26.7	496	5.7	9597	21.0	83.7	94.8
2027	5250	2105	4	1470	26.8	516	5.8	954	21.0	83.6	94.8
2028	5232	2121	6	1486	27.1	533	6.1	953	20.9	83.5	94.7
2029	5229	2128	3	1485	27.0	537	6.1	948	20.9	83.4	94.7
2030	5216	2131	12	1504	27.2	559	6.4	945	20.8	83.4	94.7
2031	5211	2145	3	1516	27.3	570	7.2	946	20.2	83.3	94.7
2032	5205	2149	5	1528	27.5	585	7.5	943	20.0	83.3	94.7
2033	5207	2147	5	1545	28.5	604	8.6	941	19.8	83.2	94.7
2034	5194	2160	5	1564	27.7	618	8.9	946	19.8	83.2	94.6
2035	5179	2173	7	1575	28.9	628	9.2	947	19.8	83.1	94.6

Table D-34. Predicted bridge-level conditions by analysis year (Scenario 4.a).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.1	76.9	91.9
2015	4437	2449	473	1835	33.1	435	9.0	1400	24.1	76.8	93.3
2016	4612	2279	468	1792	32.5	471	9.6	1321	22.9	77.2	94.4
2017	4706	2208	445	1738	32.3	484	10.0	1254	22.3	77.2	94.5
2018	4816	2130	413	1712	32.5	503	11.4	1209	21.0	77.3	94.5
2019	4872	2106	381	1702	32.7	508	11.9	1194	20.8	77.4	94.4
2020	4875	2114	370	1765	33.1	587	12.1	1178	21.0	77.6	94.4
2021	4895	2119	345	1761	33.2	602	12.0	1159	21.2	77.7	94.4
2022	4946	2108	305	1742	33.1	576	11.8	1166	21.3	77.9	94.4
2023	4979	2144	236	1704	32.6	539	11.2	1165	21.4	78.3	94.4
2024	5004	2145	210	1700	32.3	530	10.5	1170	21.8	78.8	94.5
2025	4973	2187	199	1710	32.2	544	9.6	1166	22.6	79.3	94.7
2026	4976	2208	175	1708	31.5	541	8.8	1167	22.7	79.8	94.9
2027	4959	2234	166	1721	30.5	552	8.8	1169	21.7	80.1	94.8
2028	5021	2239	99	1658	30.0	491	8.1	1167	21.9	80.6	95.0
2029	5006	2278	75	1657	29.1	490	7.2	1167	21.8	81.3	95.2
2030	5005	2300	54	1641	28.5	476	6.5	1165	22.0	81.7	95.4

Table D-34. Predicted bridge-level conditions by analysis year (Scenario 4.a). (Continued)

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
2031	5042	2289	28	1605	27.9	461	6.1	1144	21.8	82.1	95.5
2032	5039	2296	24	1604	27.2	454	5.1	1150	22.1	82.7	95.8
2033	5081	2258	20	1571	26.8	448	4.8	1123	21.9	83.1	96.0
2034	5308	2044	7	1434	25.9	431	4.8	1003	21.2	83.5	95.9
2035	5344	2010	5	1411	25.6	435	4.8	976	20.8	83.6	95.9

Table D-35. Predicted bridge-level conditions by analysis year (Scenario 4.b).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.2	76.9	91.9
2015	4248	2572	539	1915	34.3	518	10.3	1397	24.0	75.6	91.8
2016	4270	2463	626	1961	34.4	649	11.9	1312	22.4	75.3	92.5
2017	4290	2353	716	2071	35.4	831	14.7	1240	20.7	74.9	92.9
2018	4396	2190	773	2105	36.6	927	16.5	1178	20.1	74.8	93.1
2019	4409	2133	817	2153	37.3	1013	18.9	1140	18.4	74.3	93.0
2020	4447	2098	814	2192	38.0	1080	19.9	1112	18.1	73.9	92.8
2021	4491	2059	809	2196	38.1	1096	20.0	1100	18.1	73.5	92.6
2022	4556	2011	792	2138	38.0	1031	19.8	1107	18.2	73.3	92.4
2023	4558	2043	758	2120	37.9	1007	19.6	1113	18.2	73.2	92.2
2024	4531	2056	772	2137	38.0	1025	19.4	1112	18.6	72.9	92.0
2025	4537	2065	757	2152	37.8	1041	19.2	1111	18.6	72.8	91.8
2026	4538	2088	733	2146	37.6	1034	19.0	1112	18.6	72.9	91.6
2027	4563	2101	695	2123	37.4	1001	18.8	1122	18.5	72.8	91.4
2028	4567	2093	696	2114	37.0	992	18.5	1122	18.5	73.0	91.3
2029	4566	2110	683	2092	37.0	968	18.3	1124	18.7	73.1	91.2
2030	4532	2141	686	2104	36.8	975	17.9	1129	18.9	73.2	91.0
2031	4531	2162	666	2106	36.7	969	17.7	1137	19.0	73.3	90.9
2032	4531	2170	658	2123	36.5	968	17.5	1155	19.0	73.4	90.8
2033	4540	2175	644	2117	36.4	954	17.2	1163	19.2	73.5	90.7
2034	4566	2177	616	2096	36.2	914	16.8	1182	19.4	73.7	90.7
2035	5589	1766	4	1227	23.8	253	3.0	974	20.7	84.2	96.7

Table D-36. Predicted bridge-level conditions by analysis year (Scenario 5).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	1507	719	131	664	35.5	113	8.9	551	26.6	75.8	91.6
2015	1823	529	5	423	28.7	45	3.2	378	25.5	82.5	96.2
2016	1822	532	3	423	27.4	43	1.9	380	25.6	83.0	96.6
2017	1814	540	3	429	27.5	47	1.9	382	25.6	82.8	96.6
2018	1811	543	3	435	27.8	51	2.8	384	25.0	82.7	96.5
2019	1800	557	0	437	26.4	56	1.4	381	25.0	83.4	96.6
2020	1787	569	1	456	27.5	73	2.1	383	25.5	83.3	96.5
2021	1781	575	1	468	28.3	86	2.8	382	25.4	83.2	96.4
2022	1779	578	0	479	28.8	96	3.2	383	25.5	83.1	96.3
2023	1765	590	2	497	29.0	119	3.6	378	25.3	82.8	96.2
2024	1760	597	0	496	28.9	119	3.6	377	25.3	82.7	96.2
2025	1754	602	1	499	27.4	125	4.2	374	23.2	83.1	96.2
2026	1749	608	0	498	28.3	125	5.1	373	23.1	82.8	96.1
2027	1748	609	0	498	28.2	126	5.1	369	23.0	82.8	96.1
2028	1748	609	0	493	28.1	126	5.1	367	23.0	82.7	96.0
2029	1746	611	0	492	28.1	127	5.2	365	22.9	82.6	96.0
2030	1743	614	0	493	27.1	128	5.2	365	22.9	82.6	95.9
2031	1739	618	0	491	27.9	127	5.2	363	22.7	82.6	95.9
2032	1739	616	2	489	27.9	129	5.2	360	22.9	82.5	95.9
2033	1740	616	1	483	27.8	124	5.2	359	22.6	82.4	95.9
2034	1739	617	1	481	27.8	121	5.1	360	22.7	82.4	95.9
2035	1738	619	0	478	27.7	119	5.1	359	22.6	82.4	95.8

Table D-37. Predicted bridge-level conditions by analysis year (Scenario 6).

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
Base	4282	2606	471	1824	32.8	330	7.6	1494	25.1	76.9	91.9
2015	4915	2154	290	1562	30.7	280	7.0	1282	23.7	78.6	94.6
2016	4881	2152	326	1592	31.0	345	7.9	1247	23.0	78.2	94.9
2017	4885	2124	350	1617	31.2	400	9.1	1217	22.1	77.9	94.8
2018	4870	2118	371	1661	31.9	457	10.2	1204	21.5	77.6	94.6
2019	4825	2140	394	1710	32.6	525	11.2	1185	21.3	77.3	94.4
2020	4805	2152	402	1795	33.7	625	12.2	1170	21.4	77.0	94.2
2021	4788	2155	416	1837	33.8	689	12.4	1148	21.4	77.2	94.2

Table D-37. Predicted bridge-level conditions by analysis year (Scenario 6). (Continued)

Year	Good	Fair	Poor	SD/FO Bridges		SD Bridges		FO Bridges		SR	HI
				# Bridges	% Deck Area	# Bridges	% Deck Area	# Bridges	% Deck Area		
2022	4776	2163	420	1861	34.2	709	12.9	1152	21.3	77.0	94.0
2023	4796	2172	392	1892	34.5	738	12.8	1154	21.7	77.0	93.9
2024	4778	2198	383	1897	34.3	750	12.7	1147	21.6	77.0	93.8
2025	4785	2213	361	1899	34.3	750	12.7	1149	21.6	77.1	93.8
2026	4808	2213	338	1878	34.3	724	12.6	1154	21.7	77.1	93.7
2027	4789	2252	318	1880	34.2	719	13.3	1161	20.9	77.2	93.6
2028	4793	2264	302	1901	34.2	740	13.0	1161	21.2	77.3	93.6
2029	4786	2285	288	1870	34.2	704	12.9	1166	21.2	77.2	93.4
2030	4769	2318	272	1894	32.8	692	11.6	1172	21.2	78.0	93.9
2031	4767	2336	256	1898	32.7	724	11.5	1174	21.2	78.1	93.8
2032	4772	2345	242	1851	32.5	662	11.2	1189	21.4	78.0	93.7
2033	4782	2351	226	1844	32.3	653	11.2	1191	21.2	78.1	93.7
2034	4793	2367	199	1877	31.5	672	9.2	1205	22.2	79.3	94.3
2035	4785	2383	191	1831	31.3	621	9.2	1210	22.1	79.3	94.2

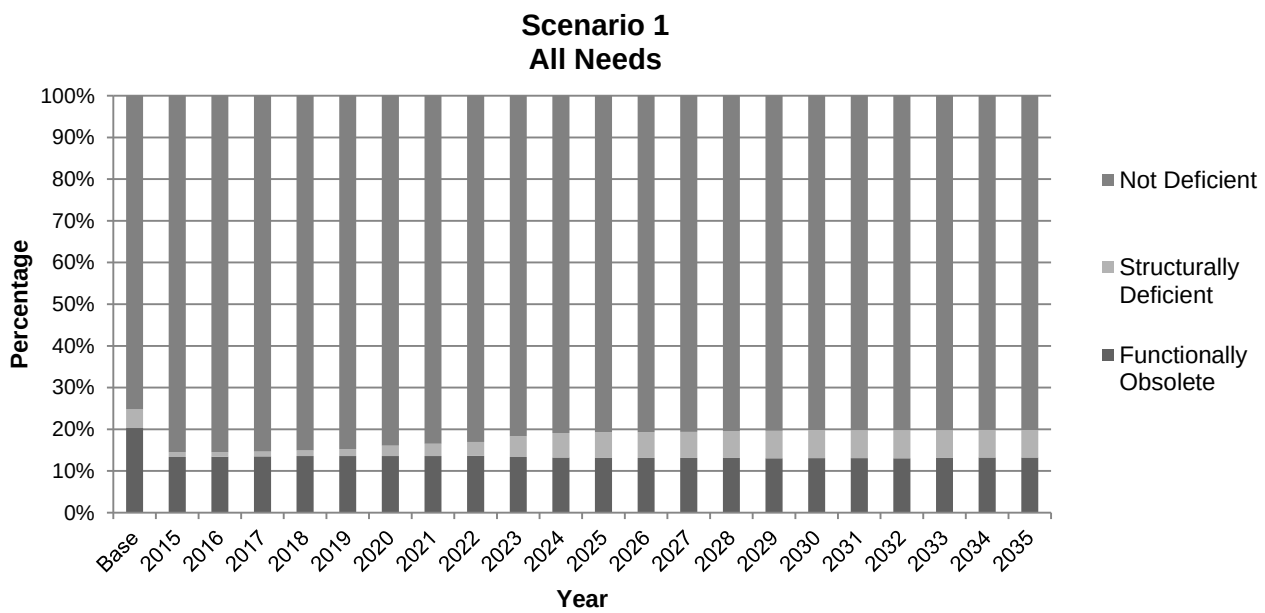


Figure D-37. Percentage of structurally deficient or functionally obsolete bridges (Scenario 1).

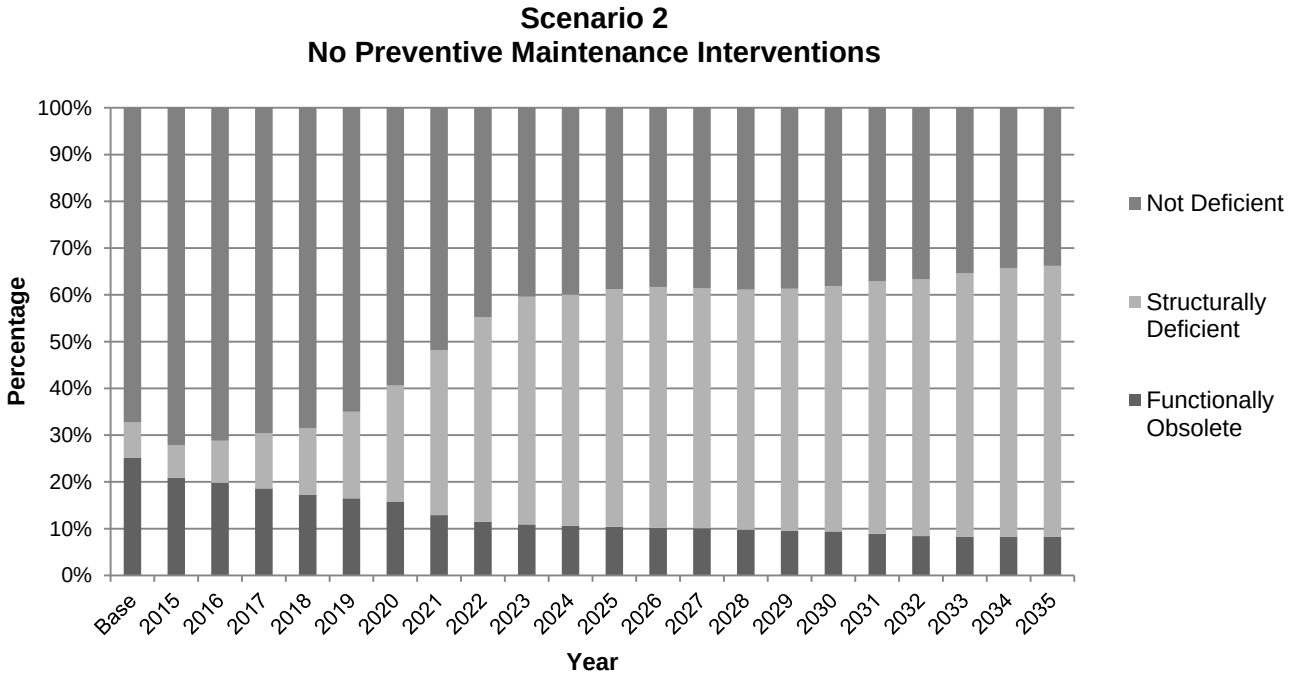


Figure D-38. Percentage of bridges identified as Structurally Deficient or Functionally Obsolete (Scenario 2).

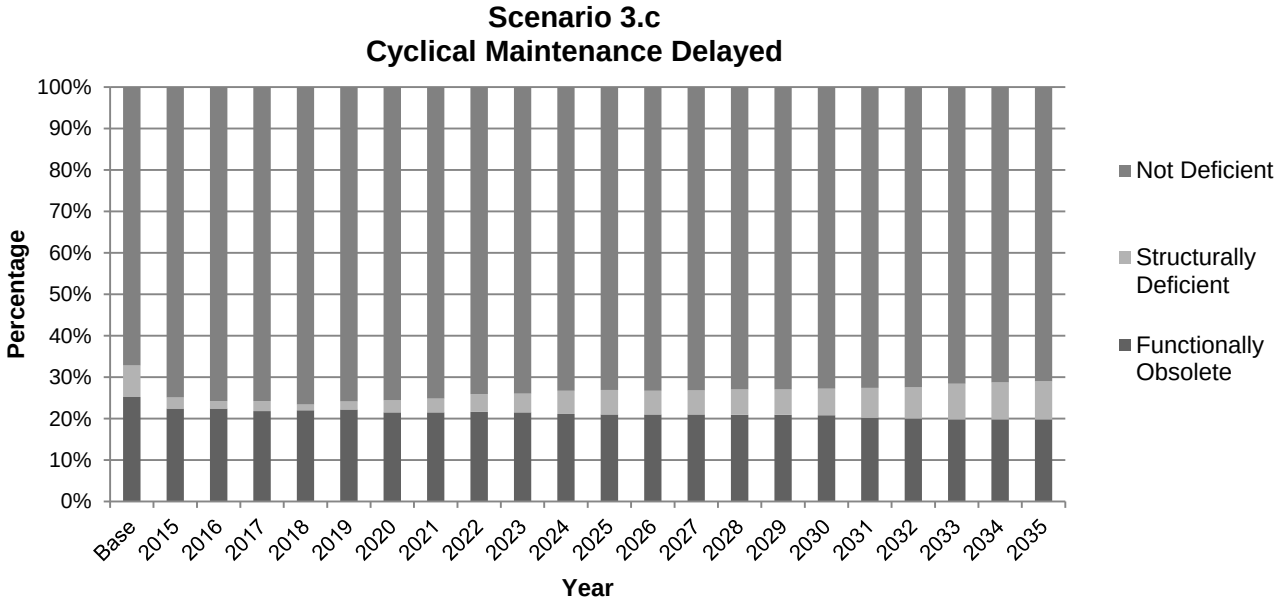


Figure D-39. Percentage of bridges identified as Structurally Deficient or Functionally Obsolete

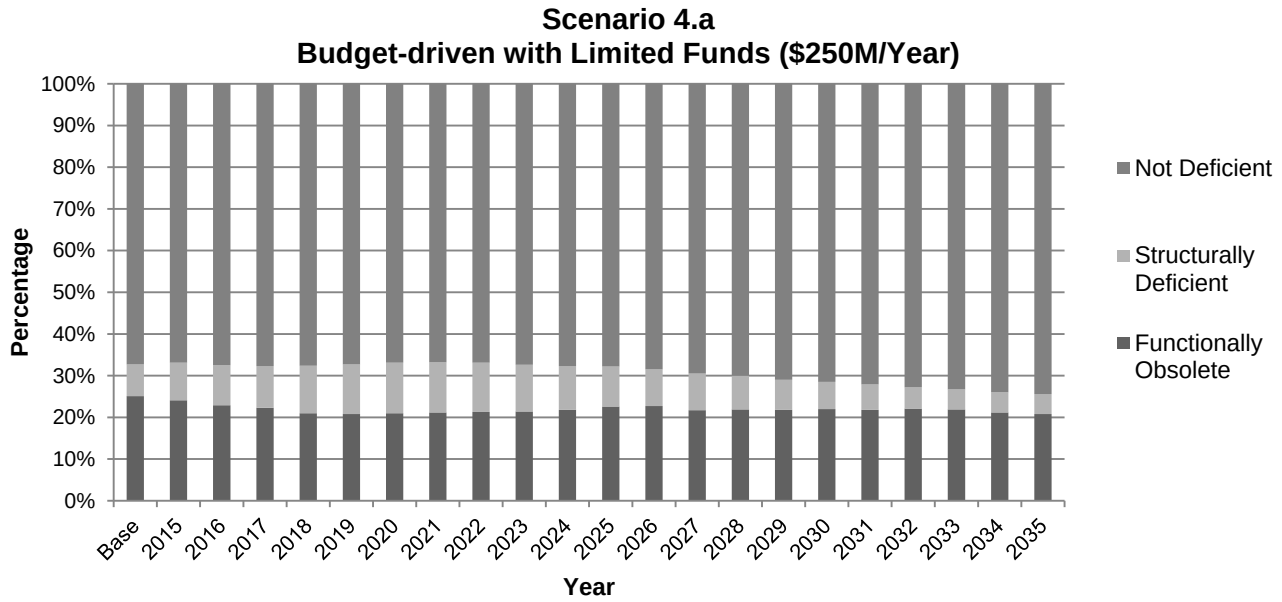


Figure D-40. Percentage of bridges identified as Structurally Deficient or Functionally Obsolete (Scenario 4.a).

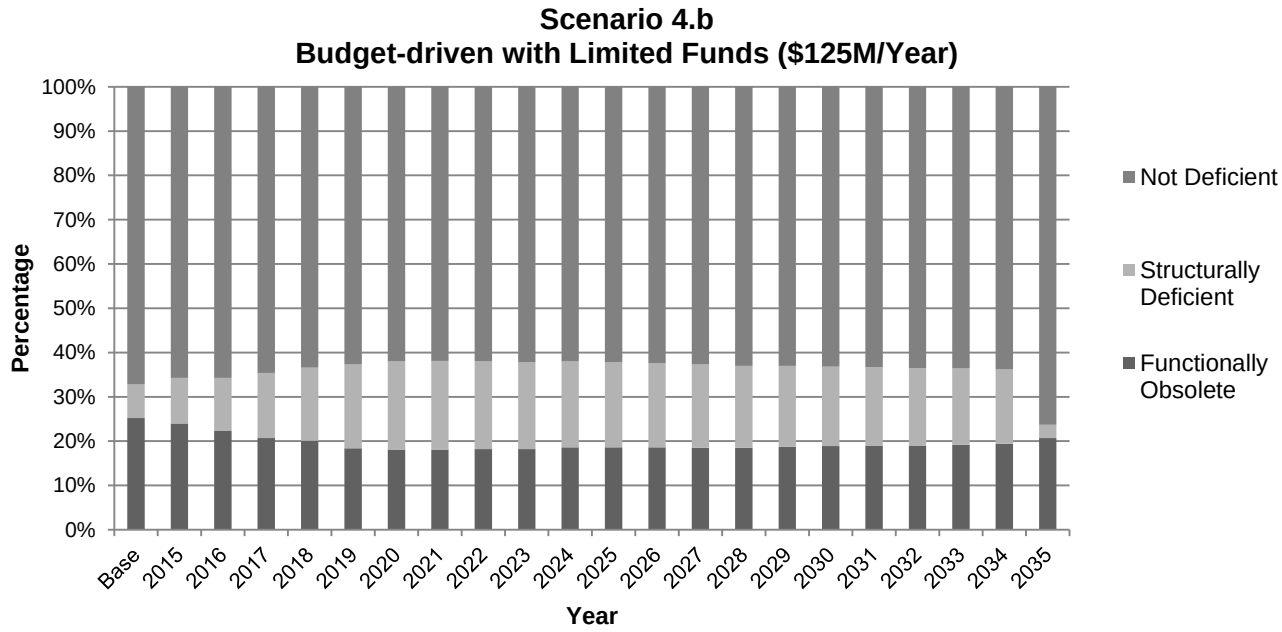


Figure D-41. Percentage of bridges identified as Structurally Deficient or Functional Obsolete (Scenario 4.b).

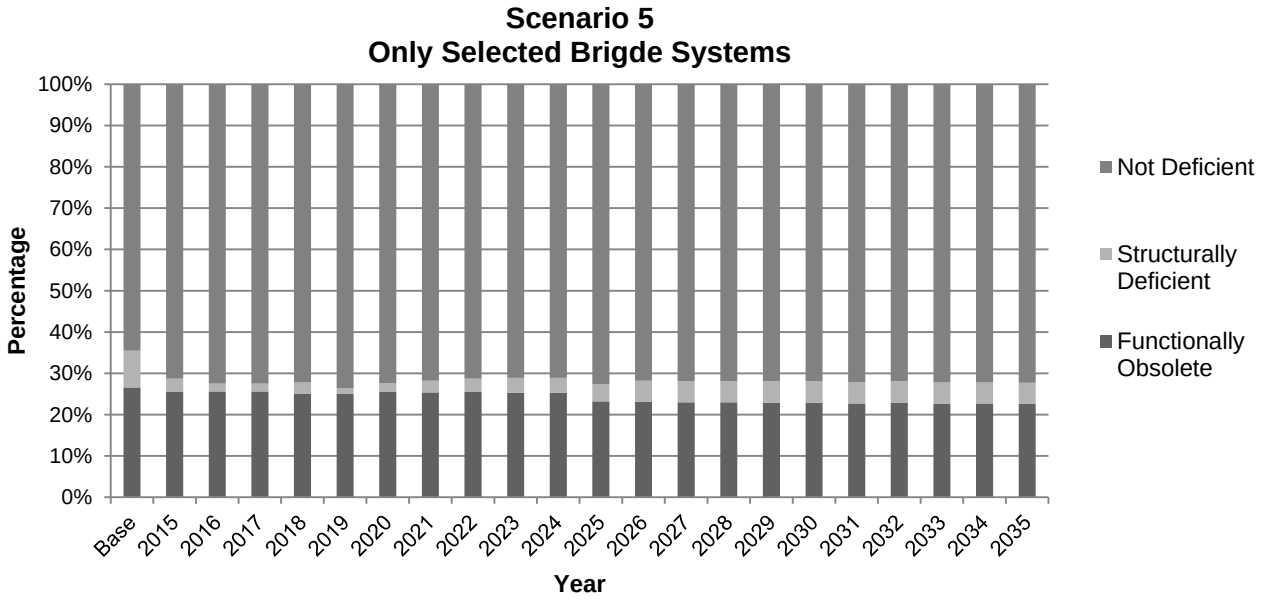


Figure D-42. Percentage of bridges identified as structurally deficient or functionally obsolete (Scenario 5).

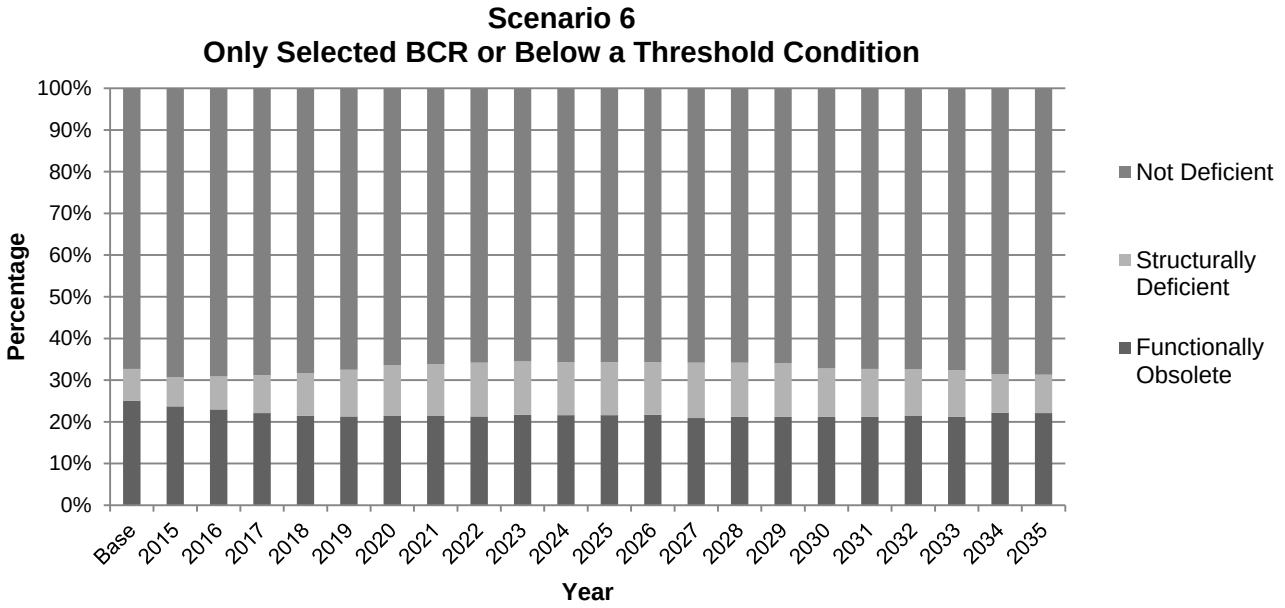


Figure D-43. Percentage of bridges identified as structurally deficient or functionally obsolete (Scenario 6).

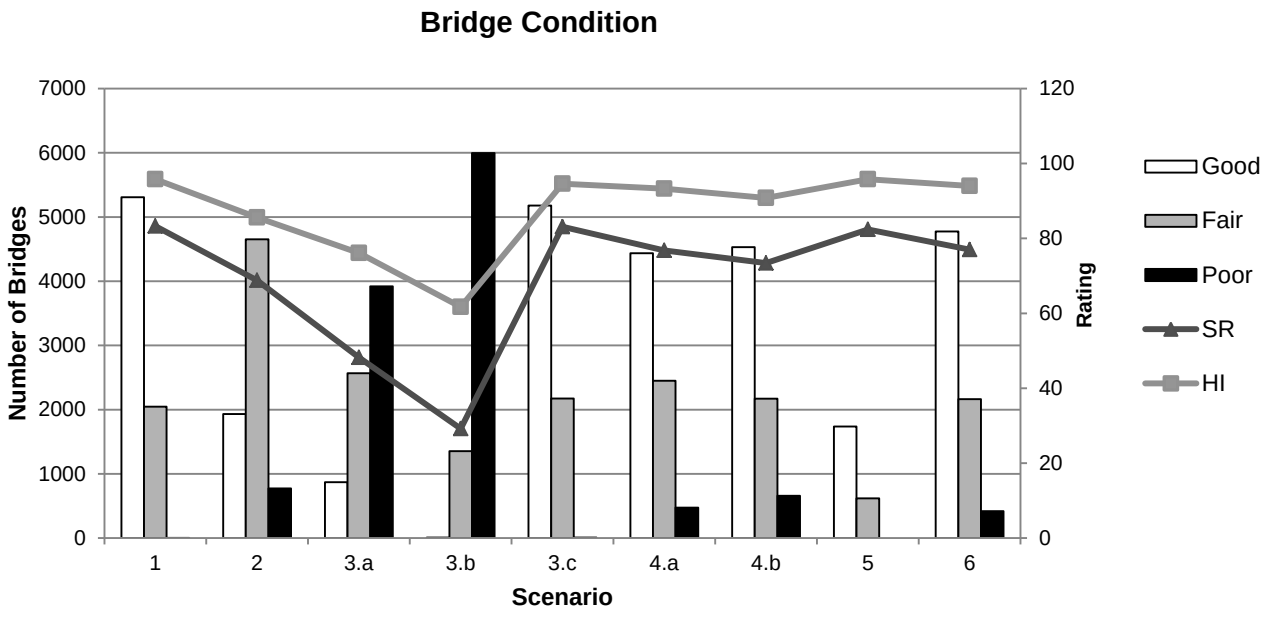


Figure D-44. Bridge condition, Sufficiency Rating, and Health Index at the end of deferral period.

D.6.7 Determine the Impact and Report the Consequences of Delayed Maintenance

Table D-38 reiterates the nine scenarios that were run for this example, as described previously in Table D-12. Table D-39 shows the summary results for the scenarios. As noted above, all of the scenarios, when compared to Scenario 1, provide insights on the impacts of deferral. In all cases, either the agency costs for the total work done over time is higher as a result of deferring maintenance and/or conditions are worse at the end of the analysis period. However, in some cases it can be difficult to compare the scenarios without additional context. For instance, Scenario 3.c quantifies the impact of delaying cyclical maintenance by simulating a greater deterioration rate than that in Scenario 1, but NBIAS does not actually quantify the cost of this cyclical maintenance, complicating interpretation of the results. Specific additional issues are noted in the table that one should consider in reviewing results of each of the scenarios.

Table D-38. Description of maintenance scenarios.

Scenario	Definition	Description
1	All needs	Maintenance, rehabilitation and replacement work is performed as needed to meet the performance targets established by the agency.
2	No Preventive Maintenance Interventions for components in fair or better condition eliminated	The impact of shifting away from a preventive maintenance strategy is modeled by creating an alternative maintenance policy that eliminates interventions for components in fair or better condition.
3	Delayed maintenance treatments	
	a. 10 years delay	Maintenance treatments are delayed by 10 years.
	b. 20 years delay	Maintenance treatments are delayed by 20 years.
	c. Cyclical maintenance delayed	Cyclical maintenance actions are assumed to be deferred, resulting in more rapid deterioration of elements impacted by cyclical maintenance activities (e.g., decks and joints.
4	Budget-driven with limited funds	
	a. Maintenance $250M budget scenario	Maintenance treatments are performed assuming that there are limited funds to implement the agency's desired maintenance plan. The budget was limited to $250M/year for 20 years. Treatments are prioritized by the system based on incremental benefit/cost.
	b. Maintenance $125M budget scenario	Maintenance treatments are performed assuming that there are limited funds to implement the agency's desired maintenance plan. The budget was limited to $125M/year for 20 years. Treatments are prioritized by the system based on incremental benefit/cost.
5	Only selected bridge systems.	Maintenance treatments are performed only for selected bridge systems (e.g., interstates or NHS).
6	Only selected benefit/cost ratio or below a threshold condition.	Maintenance treatments are performed only above a threshold benefit/cost ratio or below a threshold condition.

Table D-39. Summary of results for the scenario analysis.

Scenario	Agency Costs for Total Work Performed (including replacements) ($M)	Backlog of Needs at the end of deferral period ($M)	User Benefits Obtained from MR&R ($M)	Agency Costs for Maintenance Repair and Rehabilitation (MR&R) - ($M)	Health Index at the end of deferral period	Structurally Deficient Deck Area at end of deferral period (%)
Scenario 1	5,098	0	161	1,513	96	8
Scenario 2[1]	6,475	2,231	429	431	85	57
Scenario 3.a	11,453	9,882	53	854	76	91
Scenario 3.b	17,436	17,257	1	30	62	100

Table D-39. Summary of the results for the scenario analysis. (Continued)

Scenario	Agency Costs for Total Work Performed (including replacements) ($M)	Backlog of Needs at the end of deferral period ($M)	User Benefits Obtained from MR&R ($M)	Agency Costs for Maintenance Repair and Rehabilitation (MR&R) - ($M)	Health Index at the end of deferral period	Structurally Deficient Deck Area at end of deferral period (%)
Scenario 3.c[2]	5,648	297	185	2,052	95	9
Scenario 4.a[3]	5,138	2,910	138	1,383	93	12
Scenario 4.b[3]	5,421	3,673	132	1,156	91	20
Scenario 5	8,926	5,508	141	1,019	70	76
Scenario 6[4]	3,730	2,432	138	1,369	93	13

Notes:
[1] Backlog remains higher than the baseline ($2,122M) and conditions remain lower at the end of the deferral period based on the different MR&R policy used for this scenario.
[2] Cost of cyclical maintenance that is deferred is not estimated here – only the impacts of deferral
[3] Backlog and conditions at the end of the deferral period differ from the baseline due to the budget assumptions used for this scenario.
[4] Backlog remains higher than the baseline ($1,225M) at end of deferral period based on benefit/cost cutoff used

Given the manner in which NBIAS performs its modeling, scenarios 3.a and 3.b are the most straightforward to interpret. In these scenarios, NBIAS defers all work but the system does not calculate a penalty for deferring needed functional improvements or replacement, only for deferring maintenance work. At the end of the deferral period the system is allowed to perform all needed work to bring the system conditions to approximately the same value as the baseline, in many cases modeling replacement of bridges for which maintenance was deferred. With this approach, many of the impacts of delaying maintenance are thus monetized.

Table D-40 shows the net benefit and benefit/cost ratio calculations of the baseline scenario relative to deferral for each of these scenarios. The benefit/cost ratio (BCR) for performing needed maintenance is calculated as the net benefit of performing maintenance work (sum of the agency costs increase in for total work done and reduction in user benefits from maintenance work) divided by the increased agency cost of performing needed maintenance rather than deferring it. The benefit totals $6.4 billion for a 10-year deferral and $12.5 billion for a 20-year deferral versus a cost for the baseline of $659 million relative to a 10-year deferral and $1,483 in the case of a 20-year deferral. The BCR of the baseline is thus 9.8 relative to deferring work for 10 years or 8.4 relative to deferring needed work for 20 years.

Table D-40. Comparison of delayed maintenance scenarios to the baseline scenario (Scenario 1).

Deferral Period	Agency Costs Increase for Total Work Done ($M)	Reduction in User Benefits Obtained from MR&R ($M)	Net Benefit of Baseline vs. Deferral ($M)	Agency Cost Reduction in MR&R Work Done ($M)	BCR of Baseline Relative to Deferral
10 years (Scenario 3.a)	6,355	108	6,463	659	9.8
20 years (Scenario 3.b)	12,338	160	12,498	1,483	8.4

The fact that the BCR is lower for the 20-year deferral appears to results from the manner in which NBIAS models bridges that require reconstruction or replacement. Specifically, the system models no increased needs

for these bridges. This feature of the system is useful for isolating costs of a shorter delay in needed maintenance, but tends to understate costs from an extended deferral, as in the case of a long deferral of maintenance, there are many additional risks from having bridges in poor condition that are not modeled in NBIAS.

Although Table D-31 is limited to comparing the baseline to scenarios 3.a and 3.b, in concept the approach demonstrated here could be extended to other scenarios, but such a direct calculation of BCR can be performed only if the results were further adjusted to account for the issues noted in Table D-39.

D.7 Summary

The following lessons were learned through the process of preparing and analyzing the results:

- It is feasible to use NBIAS to analyze the effects of delaying maintenance. However, depending on the deferral scenario one is analyzing, it may help to simplify interpretation of the results by narrowing the analysis to bridges that are candidates for maintenance work, omitting any bridges for which reconstruction or replacement is already planned.
- The most straightforward deferral scenarios to analyze using NBIAS are scenarios in which all maintenance work is deferred for a set time period. The analysis described here illustrates 10 and 20-year deferrals.
- For deferral periods longer than 10 years, there may be risks of bridge closure and other risks not captured by NBIAS. Thus, a deferral period of no more than 10 years is recommended in the practice.
- In the example analysis illustrated here, the benefit/cost ratio of performing needed work is estimated to be 9.8 relative to delaying needed maintenance for 10 years. This estimate accounts for factors modeled by NBIAS, including increased costs from needed to reconstruct or replace bridges as a result of delaying maintenance, and the loss of user benefits of maintenance work.

Reference

American Association of State Highway and Transportation Officials (AASHTO). 2013. *Guide Manual for Bridge Element Inspection*. American Association of State Highway and Transportation Officials, Washington, D.C.

Butler, B.C., R.F. Carmichael, P. Flanagan and F.N. Finn. 1986. *NCHRP Report 285: Evaluating Alternative Maintenance Strategies*. Pg. 18.

British Columbia Ministry of Transportation and Infrastructure. 2010. *Environmental Best Practices for Highway Maintenance Activities*. Canada. http://www.th.gov.bc.ca/publications/eng_publications/environment/references/Best_Practices/Envir_Best_Practices_Manual_Complete.pdf. Accessed on July 15, 2014.

Cambridge Systematics, Inc., PB Consult, Inc., and Texas Transportation Institute. 2006. *Performance Measures and Targets for Transportation Asset Management*. NCHRP Report 551. Transportation Research Board, Washington, D.C.

Cambridge Systematics, Inc. 2007. *National Bridge Investment System (NBIAS) Version 3.3, Technical Manual, Draft*. Prepared for Federal Highway Administration.

Federal Highway Administration. (FHWA). 1992. *Additional Guidance on 23 CFR 650 D*. U.S. Department of Transportation. Office of Engineering, Bridge & Structures.

Federal Highway Administration. (FHWA). 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. U.S. Department of Transportation. Office of Engineering, Bridge Division. Report No. FHWA-PD-96-001.

Federal Highway Administration (FHWA). 2011. *Bridge Preservation Guide, Maintaining a State of Good Repair Using Cost-Effective Investment Strategies*. Report No. FHWA-HIF-11-042. Federal Highway Administration, Washington, D.C.

Federal Highway Administration (FHWA). 2012. Asset Sustainability Index*: A Proposed Measure for Long-Term Performance*. *Transportation Asset Management Case Studies. Comprehensive Transportation Asset Management.* Report No. FHWA-HEP-12-046. Federal Highway Administration, Washington, DC.FHWA-HEP-12-046. Washington, D.C.

Federal Highway Administration (FHWA). 2014a. *Advancing a Sustainable Highway System: Highlights of FHWA Sustainability Activities.* Report No. FHWA-HEP-14-0. Federal Highway Administration, Washington, D.C.

Federal Highway Administration (FHWA). 2014b. *2013 Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance, Report to Congress*. Federal Highway Administration. Washington, D.C.

Georgia Department of Transportation. (GDOT). 2013. Fact Book.

Hawk, H. 2003. *Bridge Life-Cycle Cost Analysis*. NCHRP Report 483. Transportation Research Board, Washington, D.C.

Hooks J. and D. M. Frangopol. 2013. *LTBP Bridge Performance Primer*. FHWA-HRT-13-051. Federal Highway Administration, Washington, D.C.

Robert, W., A. R. Marshall, S. S. Lin, R. W. Shepard, and J. Aldayuz. 2002. *Integration of Agency Rules with the Preservation Optimization Model in the Pontis Bridge Management System*. Transportation Research Record 1795. Transportation Research Board, Washington, D.C.

Ohio Department of Transportation. (ODOT). 2008. *Development of Degradation Rates for Various Bridge Types in Ohio.University of Cincinnati Infrastructure Institute*. http://www.dot.state.oh.us/engineering/OTEC/2008%20OTEC%20Presentations/2A-Helmicki.pdf. Accessed Sep 1, 2014.

Michigan Department of Transportation. (MDOT). 2009a. Bridge Management System. Presented to Domestic Scan on Bridge Management. Webinar. https://www.nhi.fhwa.dot.gov/downloads/other/real_solutions_presentations/real_solutions_presentation_2009_11_3.pdf. Accessed Jul 10, 2014.

Michigan Department of Transportation. (MDOT). 2009b. Minnesota Statewide Transportation Policy Plan: 2009 – 2028.

Michigan Department of Transportation. MDOT. 2010. *Driven by Excellence: A Report on Transportation Performance Measurement at MDOT*. http://www.michigan.gov/documents/mdot/MDOT_DrivenExcellence. Report_323894_7.pdf. Accessed Jul 10, 2014.

Nebraska Department of Roads. NDOR. 2011. *Developing Deterioration Models for Nebraska Bridges*. Project Number: SPR-P1(11) M302.

Sobanjo J., P. Thompson. 2007. *Decision Support for Bridge Programming and Budgeting*. Florida Department of Transportation Research Center. Tallahassee, FL

Spy Pond Partners, LLC with Arora and Associates. 2010. *Measuring Performance Among State DOTs, Sharing Best Practices Comparative Analysis of Bridge Condition*. Final Report. NCHRP 20-24(37)E.

United States Department of Transportation. (USDOT). 2013. *2013 Status of the Nation's Highways, Bridges and Transit: Conditions & Performance*. Report to Congress.

Wyoming Department of Transportation. (WYDOT). 2014. *Transportation Facts 2013*.Sixteenth edition.

West Virginia Department of Transportation. (WVDOT). 2012. *Factbook*. Chapter Highways.

Zietsman, J., T. Tamani, J. Potter, V. Reeder, and J. DeFlorio. 2011. NCHRP Report 708: *A Guidebook for Sustainability Performance Measurement for Transportation Agencies*. Transportation Research Board, Washington, D.C.