APPENDIX C

Procedure to Quantify Consequences of Delayed Maintenance of Pavements

The procedure to quantify the consequences of delayed maintenance of pavements involves comparing changes in pavement condition and other performance measures under various delayed maintenance scenarios. Figure C-1 shows an overview of the procedure developed to quantify the consequences of delayed maintenance of pavements. This procedure is based on existing pavement management practices, and tools available to highway agencies. An example to illustrate the process further also is included in this Appendix.

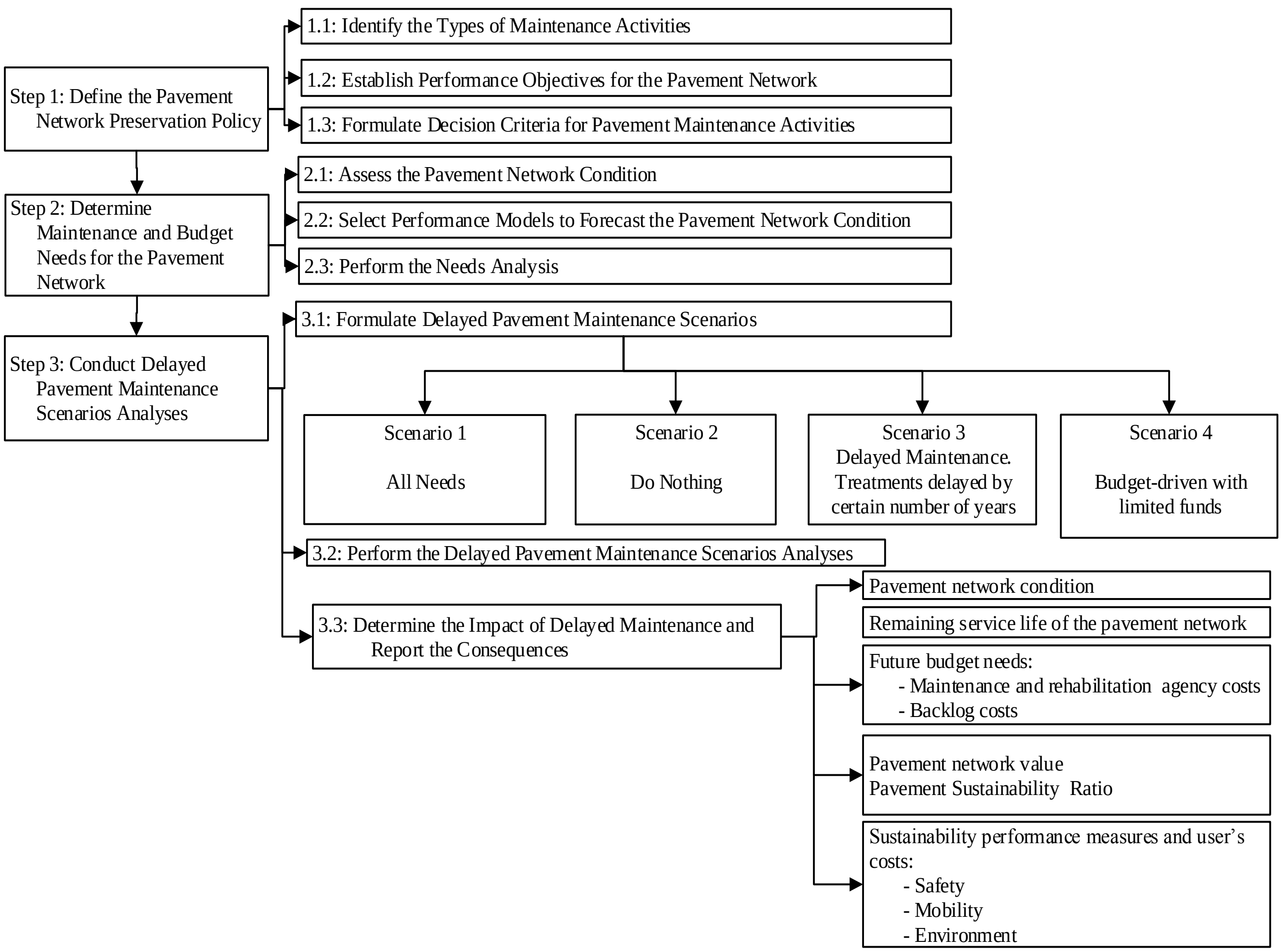


Figure C-1. Procedure to quantify the consequences of delayed maintenance of pavements.

C.1 Step 1: Define the Pavement Preservation Policy

The pavement preservation policy should define the type of treatments conducted by the agency, network-level performance measures and targets, and decision criteria (i.e., trigger values) used to formulate the preservation program. Defining the pavement preservation policy involves the following four main activities:

- Define the types of maintenance treatments
- Select performance measures
- Establish performance targets
- Formulate decision criteria (trigger values) for maintenance activities

C.1.1 Identify the Types of Maintenance Activities

Definitions of preservation and types of maintenance activities differ by agency; however, the following provides FHWA established definitions that were described in Chapter 2 but also apply to pavements:

- **Preservation** is defined as "work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair. Preservation activities generally do not add capacity or structural value, but do restore the overall condition of the transportation facility" (FHWA 2016).
- **Maintenance** is defined as "work that is performed to maintain the condition of the transportation system or to respond to specific conditions or events that restore the highway system to a functional state of operation. Maintenance is a critical component of an agencies asset management plan that is comprised of both routine and preventive maintenance" (FHWA 2016).
  - **Preventive maintenance** is defined as "a cost-effective means of extending the useful life of the Federal-aid highway (23 U.S.C. § 116 (e))" (FHWA 2016).
  - **Routine maintenance** is defined as "work that is performed in reaction to an event, season, or over all deterioration of the transportation asset. This work requires regular reoccurring attention" (FHWA 2016).

Pavement rehabilitation is defined as "structural enhancement that extend the service life of an existing pavement or improve its load carrying capability, or both" (AASHTO 2012).

- **Minor rehabilitation** "consists of non-structural enhancements to the existing pavement section" (AASHTO 2012).
- **Major rehabilitation** "consists of structural enhancements that both extend the service life of an existing pavement and/or improve its load-carrying capability" (AASHTO 2012).

Examples of maintenance treatments, as described in the *Maintenance Manual for Roadways and Bridges* are (AASHTO 2007):

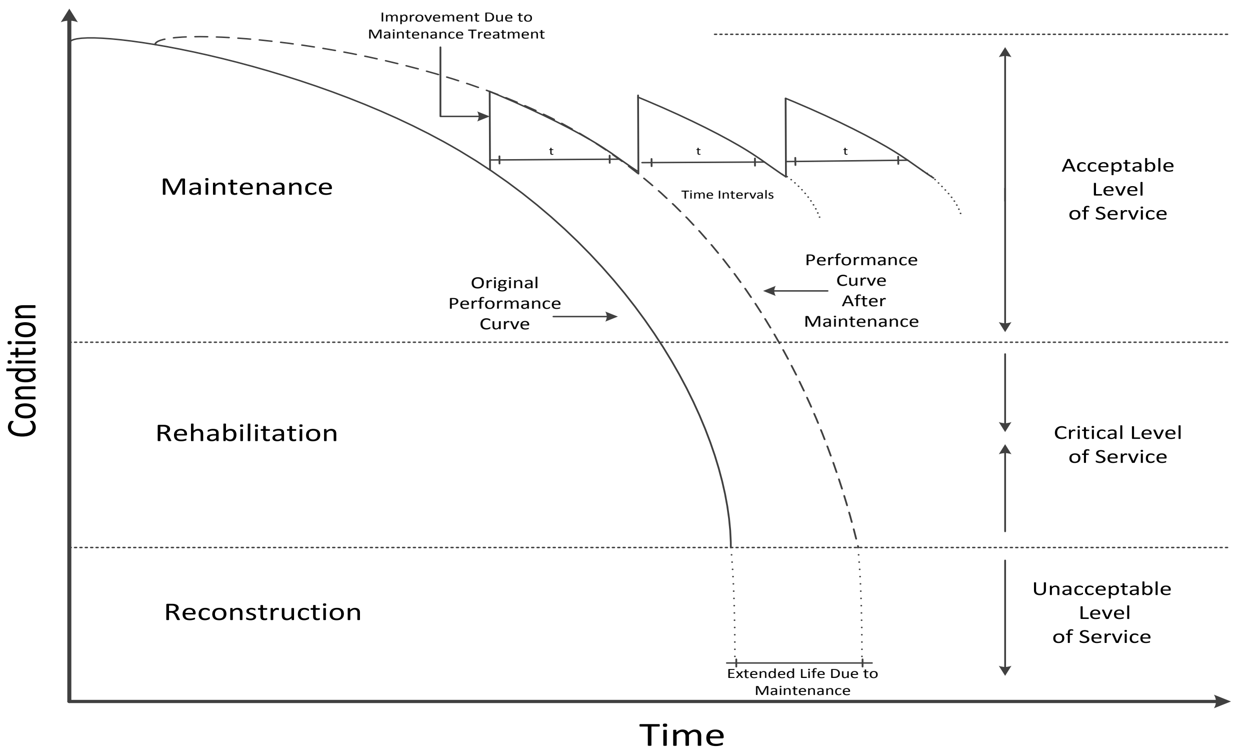
Asphalt Pavements

- Chip seals
- Cold in-place recycling
- Cold milling
- Crack filling or sealing
- Fog seal
- Hot in-place recycling
- Microsurfacing
- Patching
- Profile milling
- Thin asphalt overlays
- Scrub seals
- Slurry seals
- Ultra-thin asphalt overlay
- Ultra-thin bonded wearing course
- Ultra-thin concrete overlay

Concrete Pavements

- Crack sealing
- Diamond grinding
- Diamond grooving
- Dowel bar retrofit
- Full-depth concrete patching
- Joint resealing
- Partial-depth concrete patching
- Thin asphalt overlay
- Ultra-thin bonded wearing course

Maintenance activities alone may not be sufficient to sustain the entire pavement network in a "state of good repair". Figure C-2 shows the deterioration of the pavement condition over time and the application of treatments to preserve it in an acceptable level of service. The pavement condition gets worse if maintenance is not applied, reaching a critical level of service at which rehabilitation is needed. If rehabilitation is not applied, the pavement falls into an unacceptable level of service and reconstruction is the only option to restore the pavements structural integrity.



Source: Adapted from AASHTO 2012

Figure C-2. Pavement condition, level of service, and maintenance treatments.

C.1.2 Establish Performance Objectives for the Pavement Network

Agencies establish performance objectives when formulating their preservation programs. Performance objectives for pavements are defined by performance measures and expressed in terms of treatment trigger values. For clarity, treatment trigger values refer to agency-specific values, typically based on pavement condition (e.g., roughness, rut depth, faulting, cracking) or age (e.g., years since last treatment), by which a treatment (maintenance, rehabilitation, and reconstruction) should be applied. Performance targets refer to the threshold value for the performance measure, and performance measure is, preferably, a quantitative indicator of the level of service (e.g., quality of ride, safety, system condition) provided to the user and established by the agency.

Pavement condition affects the functional, structural, and safety performance of the pavements. According to AASHTO, pavement condition data are characterized into three main categories: surface characteristics, distress, and structural capacity. Surface characteristics data are related to pavement smoothness and surface texture. Distress data refer to observations of visible conditions on the pavement surface. Structural capacity data refers to the ability of the pavement to withstand loads (AASHTO 2012). Table C-1 presents an overview of the more commonly used performance measures related to pavement condition.

Table C-1. Pavement performance measures related to physical condition.

Performance Measure	Condition Data Category	Description
International Roughness Index (IRI)	Surface	IRI is "an index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h)" (ASTM 2012). It is related to pavement smoothness that affects the riding comfort when traveling. DOTs are required to report the IRI to FHWA every year since 1993 as part of the HPMS data submittal.
Pavement Condition Index (PCI)	Surface	PCI is "a numerical rating of the pavement condition that ranges from 0 to 100 with 0 being the worst possible condition and 100 being the best possible condition" (ASTM 2011).
Present Serviceability Index (PSI)	Surface	PSI measures the pavement "ability to serve the type of traffic which use the facility" (AASHTO 1993). It ranges from 0 (collapsed road) to 5 (perfect road). It is obtained from a mathematical combination of certain physical measurements (e.g., rut depth, cracking, slope variance). This performance measure is related to the functional pavement capacity to provide a smooth ride.
Present Serviceability Rating (PSR)	Surface	PSR is "a mean rating of the serviceability of a pavement (traveled surface) established by a rating panel under controlled conditions. The accepted PSR scale for highways is 0 to 5, with 5 being excellent" (ASTM 2012). PSR is an indicator of the riding comfort of the users when traveling the roadway section.
Skid Number (SN) or Friction Number (FN)	Surface	ASTM started the use of the Skid Number (SN) (ASTM E 274) in 1965. AASHTO adopted the ASTM E 274 test method but changed the terminology from Skid Number (SN) to Friction Number (FN). The Friction Number (FN) or Skid Number (SN), as defined in ASTM E 274 locked-wheel testing device, represents the average coefficient of friction measured across a test interval. The reporting SN values range from 0 to 100 (0 represents no friction and 100 complete friction). This performance measure is related to safety regulations. The National Highway Safety Act of 1996 mandates correction of excessive slipperiness.
International Friction Index (IFI)		In the early 1990s, the World Road Association (PIARC) developed the International Friction Index (IFI) in order to measure friction on roads. The IFI is composed of two numbers, the Friction Number (FN) and the speed number (Sp).
Cracking	Distress	There are different types of cracks including longitudinal, transverse, block or map, and edge. Longitudinal cracks are "predominantly parallel to the direction of traffic." Transverse cracks are "predominantly perpendicular to the direction of traffic." Map or block cracks are "interconnected cracks that extend only into the upper portion of the slab." Edge cracks are "crescent-shaped cracks or fairly continuous cracks that are located within 2 ft (0.6 m) of the pavement edge" (ASTM 2012).
Rutting	Distress	Rutting is "a surface depression in the wheel paths," which "stems from a permanent deformation in any of the pavement layers or subgrades, usually caused by consolidated or lateral movement of the materials due to traffic load" (ASTM 2011). Rut depth is "the maximum measured perpendicular distance between the bottom surface of the straightedge and the contact area of the gauge with the pavement surface at a specific location" (ASTM 2012).

Table C-1. Pavement performance measures related to physical condition. (Continued)

Performance Measure	Condition Data Category	Description
Faulting	Distress	Faulting is “difference in elevation across a joint or crack” (ASTM 2012). It is a common distress in jointed plain concrete pavements.
Structural Number (SN)	Structural	The SN is a function of the layers’ thicknesses, structural material coefficients, and drainage coefficients. It is a number presented in the AASHTO Guide for design of Pavement Structures (1993) that represents the pavement capacity to withstand traffic loads.
Remaining Service Life (RSL)	Distress and Structural	RSL is defined as “the time until the next rehabilitation or reconstruction event”, also as the time until a Condition Index (or distress) trigger value is reached” (Elkins et al. 2013).

Source: Adapted from Li and Kazmierowski 2004

Performance measures are used to set up objectives and to follow up the outcomes or results from the preservation programs. Examples of performance objectives include:

Network-Level Pavement Performance Objectives:
- Maximum IRI of the pavement network
- Minimum pavement condition of the pavement network
- Minimum PSI of the pavement network
- Minimum RSL of the pavement network
- Minimum percent of the pavement network in good condition
- Maximum percent of the pavement network in poor condition
- Minimum SN of the pavement network
- Minimum IFI of the pavement network

Project Level Individual Pavement Distress Objectives:
- Maximum percent of cracking allowed for a pavement section
- Maximum amount of rutting allowed for a pavement section
- Maximum amount of faulting allowed for a pavement section

C.1.3 Formulate Decision Criteria for Pavement Maintenance Activities

Maintenance activities are applied in pre-scheduled time intervals, or once the pavement condition declines to certain trigger value.

Pre-scheduled Maintenance Based on Time Intervals

Recommended treatment timing intervals as shown in Table C-2. It should be noted that the treatment timing cycles shown in this table are based on estimated expected life, and require revision based on agency experience and local maintenance practices.

Table C-2. Example of time intervals for maintenance treatment cycles.

Pavement Type	Treatment	Recommended Year of Initial Treatment	Treatment Timing Cycle
Bituminous-surfaced	Crack Sealing	1 to 3	2 to 6 years
	Fog Seals	0 to 3	1 to 2 years
	Scrub Seals	1 to 6	1 to 3 years
	Slurry Seals	2 to 6	3 to 5 years
	Microsurfacing	3 to 7	4 to 7 years
	Chip Seals	2 to 5	4 to 7 years
	Ultra-thin Friction Course	2 to 6	7 to 10 years
	Thin Overlays	5 to 8	7 to 10 years
PCC-surfaced	Joint and Crack Sealing	4 to 10	7 to 8 years
	Diamond Grinding	5 to 10	5 to 10 years

Source: adapted from Peshkin et al. 2004

Maintenance Activities Based on Condition Trigger Values

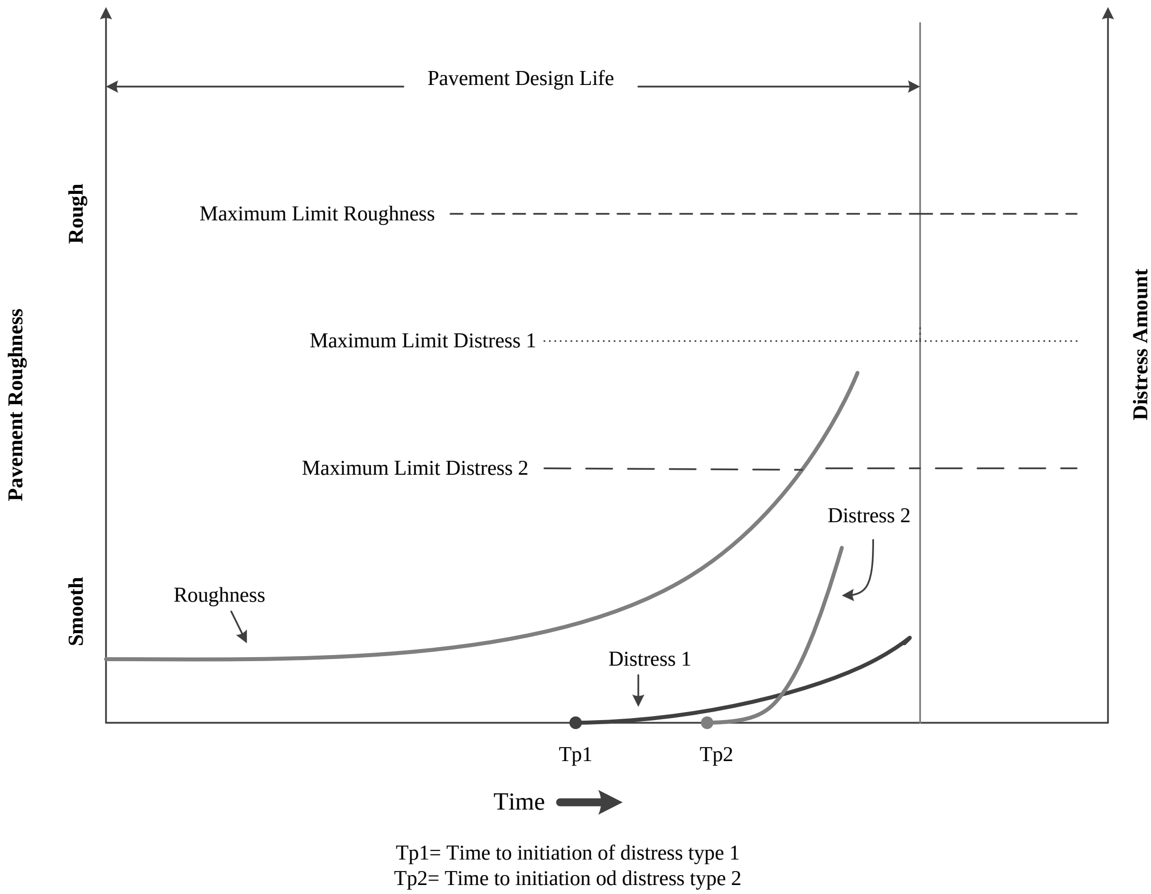
Table C-3 shows, as an example, a set of default trigger values for IRI, cracking, rutting, and faulting used in the Pavement Health Track Tool (PHT). If the amount of distress is equal to or worse than any of these trigger levels, the pavement section is a candidate for maintenance.

Table C-3. Default maintenance trigger values in PHT.

Surface Type	Class	IRI (in/mi)	Cracking		Rutting (inch)	Faulting (inch)
			Percent	Length (ft/mi)		
Flexible, Composite	Interstate	80	0	250	0.25	N/A
	Primary	100	0	1000	0.25	N/A
	Secondary	125	5	1000	0.25	N/A
Rigid	Interstate	100	0	N/A	N/A	0.10
	Primary	100	0	N/A	N/A	0.10
	Secondary	125	0	N/A	N/A	0.10.

Source: O’Toole et al. 2013

Figure C-3 illustrates another example of trigger values for maintenance activities based on roughness and individual pavement distresses.



Source: Elkins et al. 2013

Figure C-3. Example of using roughness and multiple distresses to trigger treatment interventions.

C.2 Step 2: Determine Maintenance and Budget Needs for the Pavement Network

C.2.1 Assess the Pavement Network Condition

The method selected to assess the pavement condition depends on the performance measures used by the agency. A comprehensive list of performance measures related to physical condition by data categories were listed in Table C-1. Each highway agency has its own method to assess the pavement condition, usually based on individual distresses that are often used to calculate a pavement Condition Index. Common methods to assess the pavement condition are described in the Long-Term Pavement Performance (LTPP) *Distress Identification Manual* (Miller and Bellinger 2014) and in ASTM D6433, *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. Physical pavement condition data that are usually collected include:

- Roughness (IRI)
- Distresses: cracking, faulting, rutting, rut depth, potholes
- Skid number (SN), Friction Number (FN)

An important aspect of the pavement condition assessment is the data collection method. Pavement data collection is done by walking the section, by windshield collection, or by automated surveys. Automated collection techniques include sensors, mobile digital imagining, and satellite imagining (AASHTO-AGC-ARTBA 2006). There are advantages and disadvantages for each data collection method:

Walking Surveys: The major advantage of this distress survey method is that it is highly accurate, since cracks and all other pavement distresses are measured and recorded directly. However, walking surveys are more labor-intensive and expensive than windshield surveys and potentially increase the safety risk due to raters being subjected to live traffic conditions. The LTPP project employs detailed walking surveys.

Windshield surveys: These are typically performed by two-person crews in a vehicle that travels at slower speeds. The major advantage is that 100% of the roadway is surveyed, and it can be accomplished very quickly, more safely, and inexpensively than walking surveys. However, the disadvantage is that the data collected are of variable quality. Low-severity distresses are typically not visible from a moving vehicle; and it may result in a higher condition rating of the pavements, and consequently, a lower estimate of the maintenance needs. For facilities with posted speed limits greater than 55 mph, this data collection method may require traffic control.

Automated surveys: Typically performed using a customized vehicle equipped with a video or digital camera and laser bars. The major advantage is that surveys are performed very quickly and safely. However, post-processing time may offset cost savings in the field depending on the system. The quality of the data may also vary depending on light conditions (e.g., tree-lined facilities with contrasts in light and dark); shadows can mask some distresses. NCHRP Synthesis of Highway Practice 334, *Automated Pavement Distress Collection Techniques*, offers more details about automated pavement distress data collection techniques (McGhee 2004).

C.2.2 Select Performance Models to Forecast the Pavement Network Condition

Performance models include (AASHTO 2012):

- **Distress severity and distress**: These models project individual pavement distresses. For example, the AASHTO *Mechanistic-Empirical Design Guide* (MEPDG) includes prediction models for longitudinal and transverse cracking, rutting, and faulting (AASHTO 2015). The models predict the distress severity and extent over time. These models are mainly used at the project management level.
- **Individual indices**: These models project indices related to a particular physical condition or functional performance. For example, there are models to predict the IRI based on the pavement type, traffic loads, and other factors. These models are used at the network and project management levels.
- **Composite index**: These models used indices that combine individual distresses. For example, there may be family performance models for a Condition Index for combinations of functional class and pavement types. These performance models are mainly used at the network management level.

Pavement performance can be forecast using a deterministic model that predicts a single value; a probabilistic model that predicts a range of values to express the likelihood of occurrence of a certain condition state; Bayesian models that combine objective and subjective data to predict future condition states; or expert-based models that rely upon expert opinion. Detail information about these models is included in the AASHTO Pavement Management Guide (2012).

Performance models are incorporated into pavement management systems (PMSs) already used by the highway agencies. All these models are based by default on initial construction or design and they need to be adjusted in order to reflect the individual performance trend observed over time, including the impact of a treatment in the condition and remaining service life (RSL) of a section. Figure C-4 shows an example of adjusting a deterministic model of a default Condition Index (CI) family curve for an individual pavement section based on historical values from field inspections.

Other performance models that can be used to predict the pavement condition include (AASHTO 2012):

- Probabilistic models that use transition probabilities (Markov or semi-Markov) for changes in pavement condition to account for traffic loading or environmental conditions.
- Bayesian models that complement objective data with subjective information.
- Expert-based models are based on experience and short-period pavement performance data; they are useful for new methods or materials with no historical data.

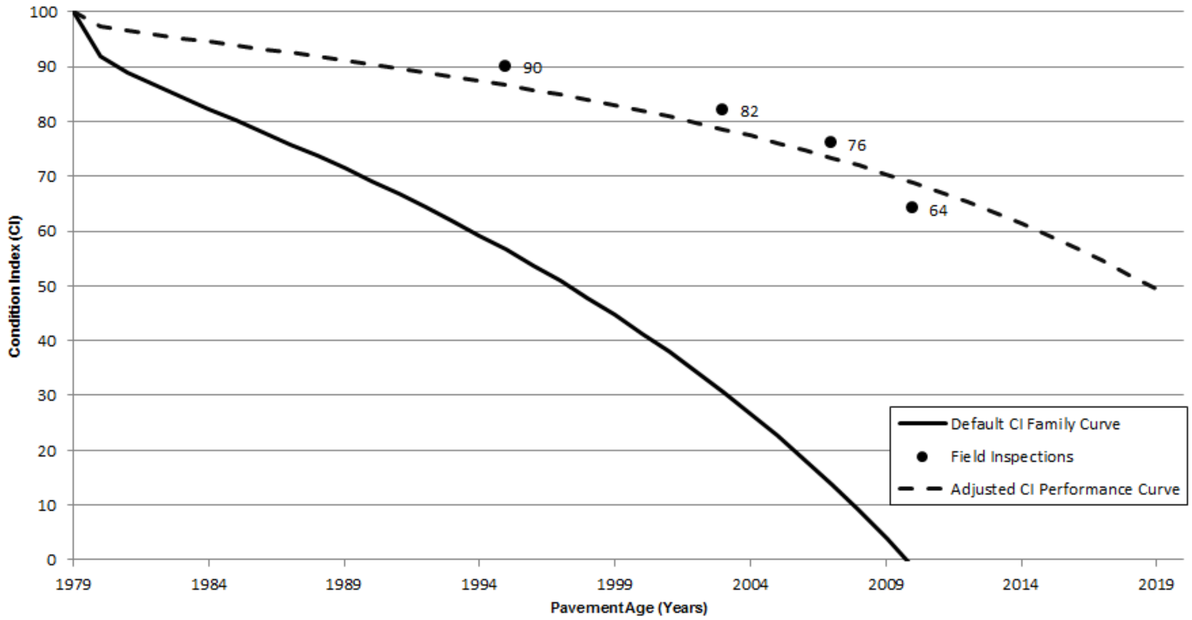


Figure C-4. Example of adjusting a family pavement performance curve for an individual section.

C.2.3 Perform the Needs Analysis

A needs analysis is performed to determine maintenance treatment and budget needs for a baseline scenario over the period of analysis. Performance models selected in C.2.2 are used to project the pavement condition over time. The analysis assumes that there are sufficient funds to implement the preferred agency's preservation policy as defined in Step 2. Figure C-5 shows a flowchart describing the process to identify maintenance treatments and budget needs.

Once the inventory is known and distresses or any other performance measures selected by the agency (e.g., IRI) are collected for the pavement network, the Condition Index is calculated for each pavement section. Trigger values based on the Condition Index or any other performance measures are used to identify pavement sections in need of maintenance or rehabilitation. Pavements in good condition can also be selected for maintenance based on pre-scheduled time intervals. A treatment is assigned based on a decision tree or a selection matrix that considers pavement condition or other performance measures. Treatment costs are calculated as well as the improvement in condition, and remaining life extension. Performance models are used to forecast the pavement condition for the next year to identify future needs. This process is repeated throughout all the years in the period of analysis. The outcome of this process is a list of pavement sections in need of treatment and corresponding budget.

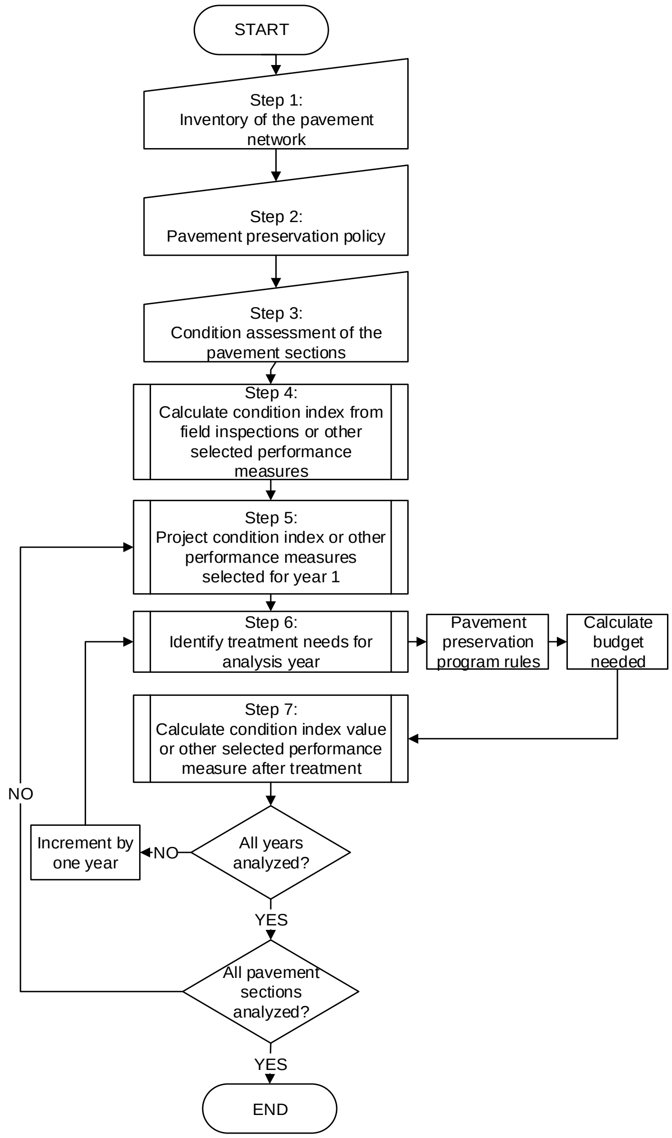


Figure C-5. Needs analysis process flowchart.

C.3 Step 3: Conduct Delayed Pavement Maintenance Scenarios Analyses

C.3.1 Formulate Delayed Pavement Maintenance Scenarios

The needs analysis in Step C.2.3 provides the baseline scenario in which there are sufficient funds to implement the agency's desired preservation plan. Delayed maintenance scenarios are compared with the baseline scenario to quantify the consequences and they include, but not limited to, the following cases:

- No maintenance treatments are applied; only major rehabilitation treatments and reconstruction are allowed. This is a second baseline scenario to evaluate the impact of no maintenance on the future pavement network condition and budget needs.
- Maintenance treatments are delayed by a certain number of years.
- Maintenance treatments are delayed until the pavement falls down into the next treatment condition category.
- Budget-driven scenarios with different levels of funding for maintenance activities.

Table C-4 shows a summary of the key elements needed to analyze the delayed maintenance scenarios for pavements. A pavement network inventory and current condition assessment is needed, as well as performance models, to perform the scenarios analyses using different types of analytical tools.

Table C-4. Key elements to analyze delayed maintenance scenarios for pavements.

Data	**Performance Models**	**Maintenance Scenarios** Length of Analysis: 20 years (*)	**Results**
Pavement network inventory with condition assessment	Deterministic Probabilistic Bayesian Expert-based model	1. All Needs 2. Do Nothing 3. Delayed maintenance a. Maintenance treatments are delayed by a certain number of years. Example: 2 years. b. Maintenance is delayed until the pavement falls down into the next treatment condition category. 4. Budget-driven with limited funds for maintenance. Examples: a. 40 percent of baseline budget needs for maintenance. b. 80 percent of baseline budget needs for maintenance.	Analytical Tools: Pavement databases and analytical tools are listed in Table C-5 as a reference. The recommendation is to use the Pavement Management System (PMS) adopted by the highway agency to perform scenarios analyses. Reports: • Agency costs over time. • Impact on pavement network condition. • Change in deferred maintenance costs over time. • Impact on remaining life. • Changes in the pavement network value and Pavement Sustainability Ratio.

(*) A 20-year analysis period is recommended since it is typical for many highway agencies.

The scenarios analysis period can be 5, 10, 20 years or even longer, and it depends on the agency planning period. However, the recommendation is to extend the length of the analysis through the first rehabilitation period after the initial design life.

C.3.2 Perform the Delayed Pavement Maintenance Scenarios Analyses

The pavement condition deteriorates and the level of service decreases when maintenance is delayed. The consequences of the delayed maintenance scenarios on pavement condition are quantified by comparing the results of the delayed maintenance scenario to the all needs scenario also called the baseline scenario. The scenarios analyses can be conducted using pavement management systems (PMSs) available at the highway agency. In addition to the agency PMSs, alternative databases and analytical tools can be used to conduct the scenario analysis (Table C-5).

Table C-5. Examples of databases and analytical tools for pavements.

Database/Tool	Developed for	Applications
Highway Performance Monitoring System (HPMS)	FHWA	• National level, performance, and condition reporting. • Pavement data: IRI, PSR, surface type, rutting, faulting, crack length, cracking percent, year last construction, year of last improvement, thickness flexible, thickness rigid, base thickness, last overlay thickness, base type, soil type, climate zone. • Traffic data: AADT combination/single unit, percent peak single/combination, Directional factor, Future AADT-year. • Also jurisdiction and geometric data, IRI thresholds: <95, 95-170, >170.
Highway Economic Requirements System (HERS)	FHWA	• Scenarios: minimum benefit-cost ratio (BCR), constraint by funds, target performance, full needs analysis. • Deficiencies: There are 5 thresholds that the user can specify for the IRI, 5 thresholds for the PSR, and other geometric features. • Improvements: resurface, reconstruction, lanes added, capacity increase, BCRo, improvement cost. • Benefits: total, maintenance cost savings, user, travel-time savings, operating cost savings, safety benefits, crashes avoided, injuries avoided, lives saved, vehicle-miles traveled (VMT) of improved sections, pollution damage savings.
Long-Term Pavement Performance (LTPP)	FHWA	• Database of pavement performance of more than 2,500 asphalt and Portland cement concrete pavement test sections throughout the U.S. and Canada. • Routine maintenance, rehabilitation, construction activities, climatic conditions, traffic, IRI, pavement thickness, annual and monthly precipitation totals, and equivalent single-axle loads (ESALs).
Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Rehabilitation (EAROMAR)	FHWA	• Tool developed in 1970s to analyze the magnitude of the cost associated with roadway occupancy. • Determines the specific hours the roadway will be occupied by work crews annually together with the maintenance and rehabilitation cost associated with that occupancy. Impact on motorist caused by roadway occupancy is established in terms of operation costs, time costs, accident costs, and pollution effects.
Highway Development & Management (HDM-4)	World Bank	• Tool for road transport infrastructure feasibility studies and network evaluation. Includes life-cycle cost analysis (LCCA) of the recurrent maintenance but the model is not generally used for planning and programming of road maintenance works. • Net present value (NPV) for various maintenance alternatives. • Road user cost model: vehicle operating costs, time costs, accident costs – International Road Assessment Programme (iRAP), emissions.
Pavement Health Track (PHT)	FHWA	• Data input from HPMS, also material properties, four climate zones and traffic loads. • Predicts future remaining service life (RSL) for a “do nothing” scenario. • Objectives: minimum cost/benefit ratio, funds constraint (then prioritize by worst RSL, maximized BCR, or best RSL extension). • If data are not available, uses LTPP and National Climate Data Center databases as default inputs. • Distresses for HMA (IRI, rutting, cracking percent, cracking length), PCC (IRI, faulting, spalling, cracking percent), composite (IRI, cracking length). • Uses performance models developed for HERS and the National Cost Model (NAPCOM). • Critical RSL, weighted average RSL. • Trigger levels for maintenance actions.

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

The importance of reporting the consequences of delayed maintenance is to justify the effectiveness of a timely treatment, both in monetary values as well as pavement network condition. The results of the scenarios analyses are used to quantify the consequences on:

- Future pavement condition
- Future remaining service life
- Future budget needs and agency costs
- Backlogged costs
- Asset value of the pavement network
- User costs
- Sustainability performance measures (safety, mobility, environmental)

Pavement condition can be illustrated in a variety of ways. For example, representation of pavement condition for a pavement network is shown in Figures C-6 through C-9. These figures are intended as examples for the type of information that can be prepared to show the results of the analyses.

In Figure C-6, pavement condition is illustrated according to Condition Index (CI) and the percentage of lane miles or pavement sections in that condition. In this illustrative example, very good condition corresponds to a minimum CI of 85, good condition to a CI between 84 and 65, fair condition to a CI between 64 and 50, poor condition to a CI between 49 and 25, and very poor condition to a CI lower than 25. The agency can use its own Condition Index to set the limits for the pavement condition categories.

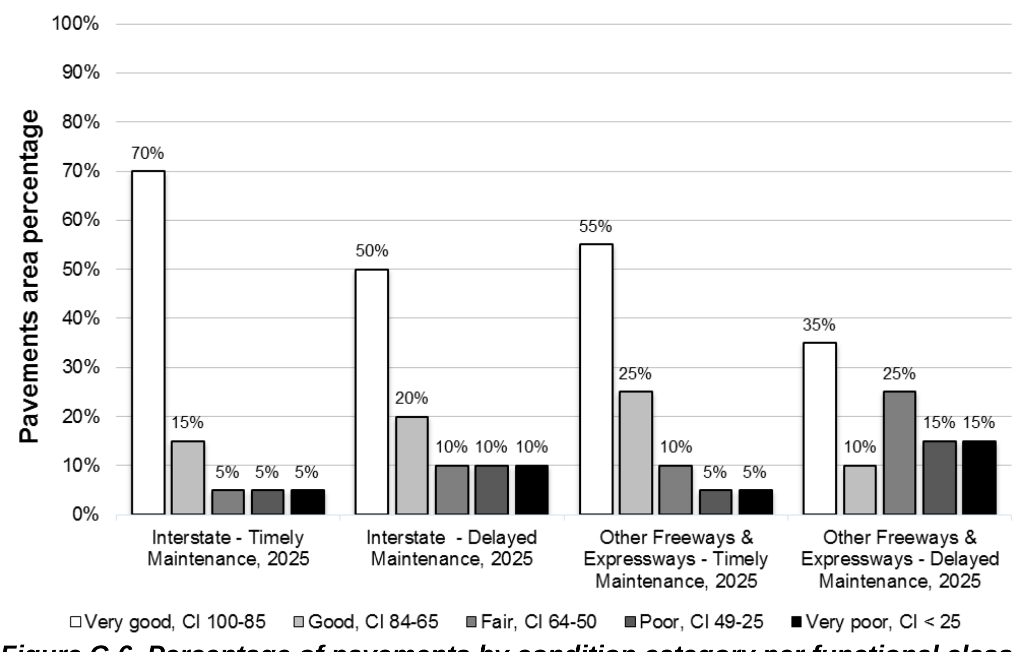


Figure C-6. Percentage of pavements by condition category per functional class.

Figures C-7 through C-9 must be prepared for different scenarios to quantify the consequences of delayed maintenance. These figures are intended as examples for the type of information that can be prepared to show the results of the analyses. Specific examples of scenarios analyses and reports provided in section C-6.

Figure C-7 illustrates how changes in the distribution of the pavement condition category by lane miles for a delayed maintenance scenario can be reported over the length of the planning period.

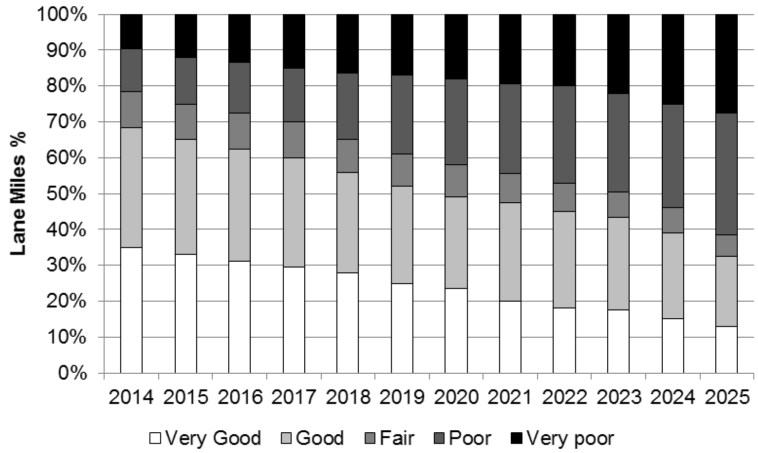


Figure C-7. Percentage of lane miles of pavements by condition category over time.

Another illustration method is shown in Figure C-8 and represents a comparison of the percentage of pavement at each condition category under different maintenance scenarios at the end of the analysis period. A 20-year analysis period is recommended since it is typical for many highway agencies.

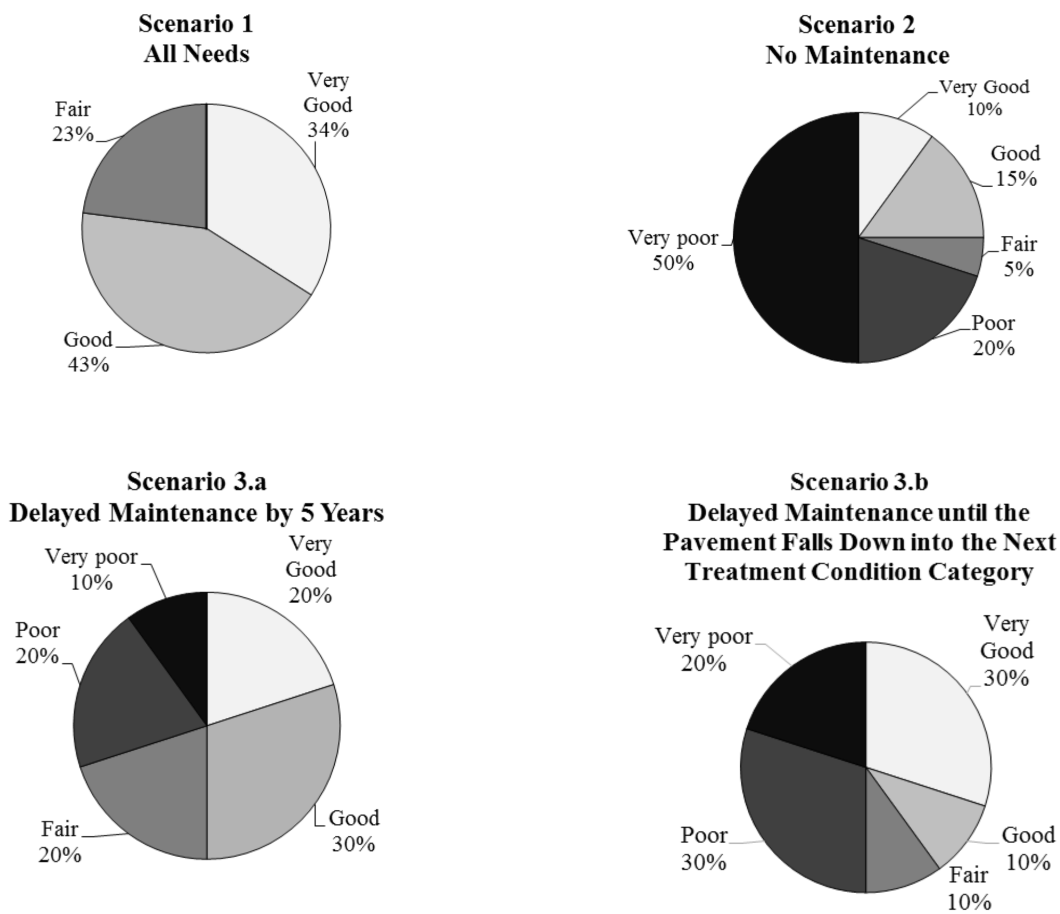


Figure C-8. Pavement condition categories at the end of the analysis period.

Finally, Figure C-9 illustrates how trends in pavement condition for a delayed maintenance scenario over time can be graphically represented. Figure C-9 shows the trend for pavement sections or percentage of lane miles in very good/good condition versus poor/very poor condition, and the performance target for the maximum percentage of roads in poor/very poor condition.

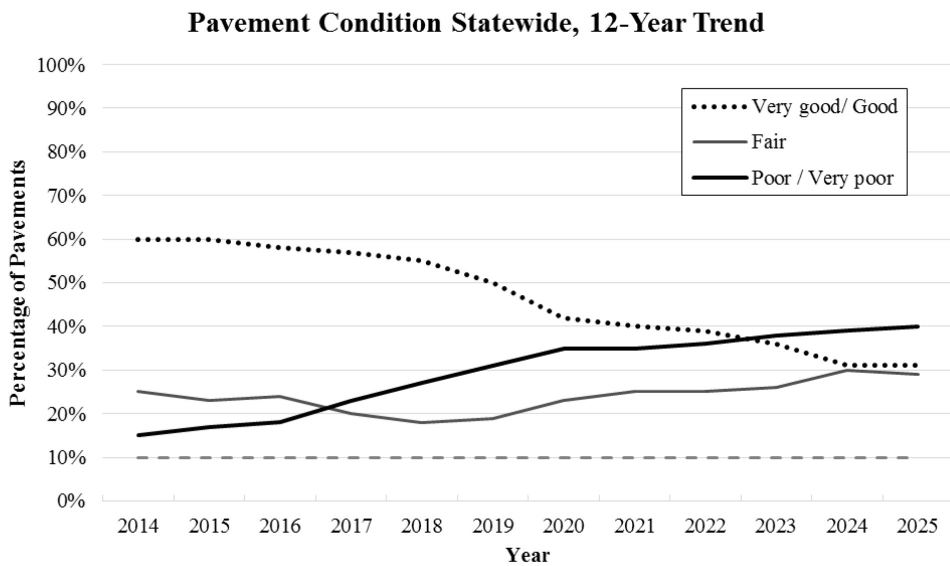


Figure C-9. Pavement condition categories over time due to delayed maintenance.

Consequences on the Remaining Service Life of the Pavement Network

The remaining service life (RSL) is defined as the time from the present (i.e., today) to when the pavement reaches an unacceptable condition requiring reconstruction (Elkins et al. 2013). The average pavement network remaining service life (RSL) at the end the analysis period due to a delayed maintenance scenario can be reported. Figure C-10 shows a mock-up example of a delayed maintenance scenario in which there is a large amount of pavement miles with less than 2 years of remaining life.

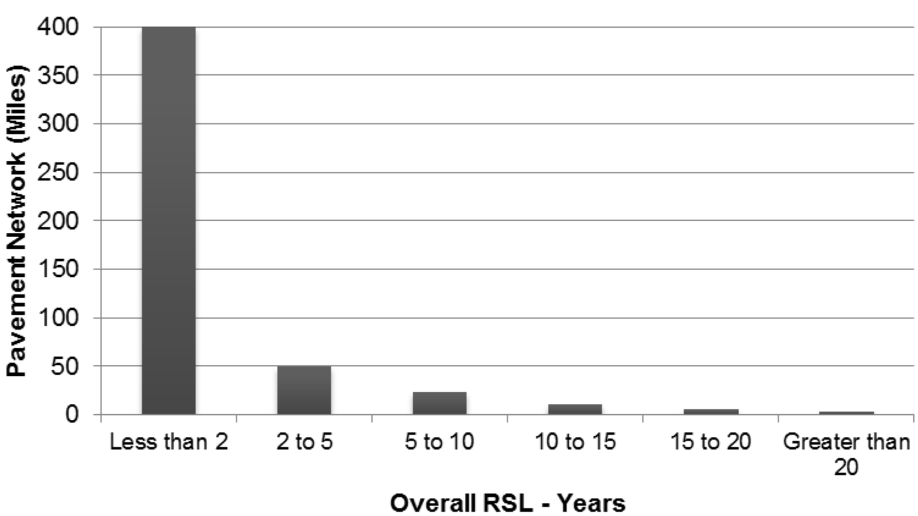
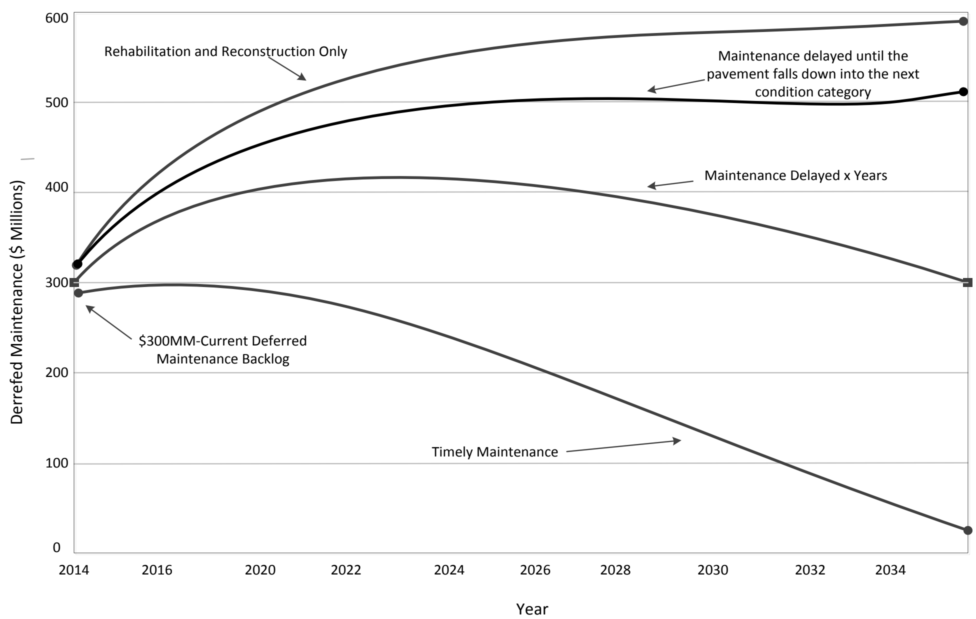


Figure C-10. Remaining Service Life (RSL) at the end of the analysis period.

Consequences on Future Budget Needs

Generally, if maintenance is delayed, more expensive treatments must be applied to restore the pavement to an acceptable condition or level of service at some future date. Funds needed to restore the pavement to the desired condition but not applied are backlogged costs. Backlogged costs are typically defined by agencies as "the cost to bring all the pavements from their current condition to a state of good repair" (NYSDOT 2008). Backlogged costs are also defined as the differences in costs between projects that were identified as needed and the projects that were actually funded (Zimmerman and Peshkin 2006). Figure C-11 shows an example of projected backlogged costs under different maintenance scenarios. Backlogged costs are estimated by the difference between needed and allocated funds.

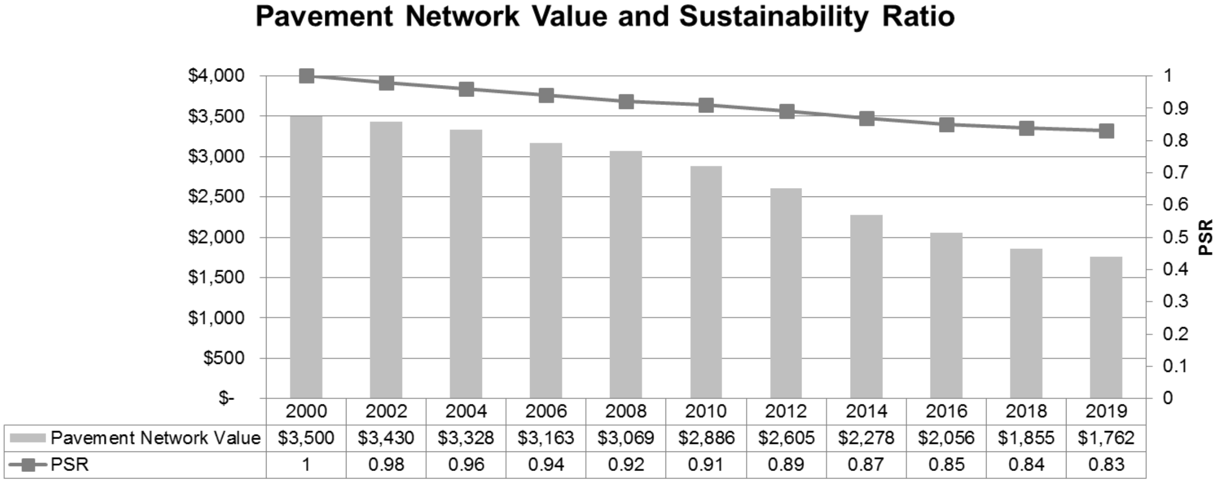


Source: Adapted from AASHTO 2012 and SDOT 2014

Figure C-11. Backlogged costs over time under different scenarios.

Consequences on the Pavement Network Value

Asset value calculations for the pavement network can be conducted using the Governmental Accounting Standards Board (GASB) Statement No. 34 guidelines as a reference, or the other asset valuation methods. The pavement network value can be reported together with a Pavement Sustainability Ratio (PSuR) for a planning period as shown in Figure C-12. PSuR is a ratio between the budget spent and funding needs to achieve the pavement network performance condition as established by the agency, where a ratio of 1 means that the allocated funds are equal to the funding needs, ratios below 1 correspond to delayed maintenance scenarios and express a decrease of the pavement network value (FHWA 2012).



Adapted from FHWA 2012

Figure C-12. Pavement network value and PSuR over time.

Consequences on Sustainability and Users' Costs

FHWA states that a sustainable highway approach is successful when "varying objectives, including safety, mobility, environmental protection, livability, and pavement network management are met while working to achieve economic targets for cost-effectiveness throughout a highway's life cycle" (FHWA 2014). Quantifying the consequences of delayed maintenance on sustainability performance measures (e.g., safety, mobility, and environment) is desired and includes users' costs. Users' costs are influenced by travel-time costs, operating costs, and accident costs, and their magnitude depends primarily on the number of users affected, traffic volume, type of vehicle, and travel speed (AASHTO 2010). Safety, mobility, and environment performance measures and users' costs approaches for pavements are introduced in this section, since they can also be considered in the scenarios analyses if data and analytical tools are available.

Safety: Analysis of the outcomes of a delayed maintenance scenario on traffic fatalities, traffic serious injuries, fatalities/vehicle miles travel ratio, motorcyclist crashes, motorcyclist injuries, motorcyclist fatalities, cyclist crashes, cyclist injuries, cyclist fatalities, pedestrian injuries, and pedestrian fatalities is encouraged. There are no tools to estimate the impact of highway condition on safety, but the Highway Safety Information System (HSIS) has an extensive inventory of crash accident records including motorcyclists, bicyclists and pedestrians; traffic and roadway inventory data that includes pavement distress and maintenance (HSIS 2014).

At the network level, safety performance can be assessed by analyzing serious injuries and fatalities data on pavement sections with delayed maintenance. Pavement sections with an extensive inventory of crash accident records in the HSIS can be identified, as well as the pavement condition and backlog costs (HSIS 2014). Backlog maintenance costs where accidents occurred can be analyzed to study if there is an effect on safety. Figure C-13 shows a generic example with mock-up data of fatalities and injuries per 100 million VMT plotted along with the backlog costs of these sections.

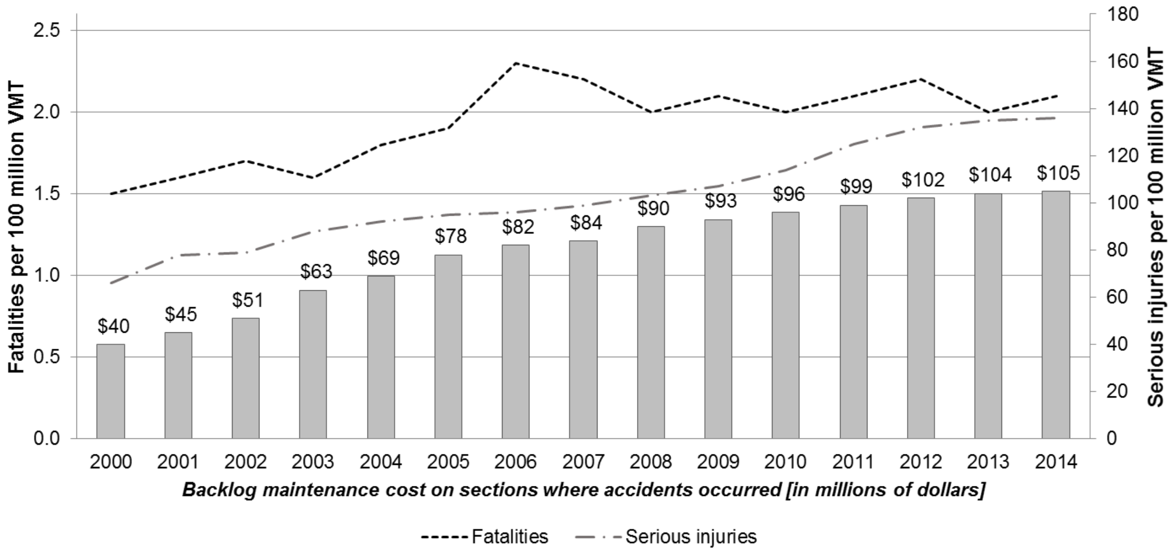


Figure C-13. Fatalities and injuries on sections with delayed maintenance.

At the project level, users' costs are established based on accident costs. A relationship between pavement condition, in terms of IRI or PSR, and crash frequency is established for this purpose. When IRI increases from 0 to 100 in/mi to 101 to 200 in/mi, the crash frequency (crashes per 100 million VMT) increases by 1.649 times, and when PSI decreases by one unit on the scale from 1 to 5, the crash frequency increases by 1.412 times (Chan et al. 2008). The AASHTO *User and Non-User Benefit Analysis for Highways Manual* provides additional guidance for studying the relationship of the user costs to accident frequency or severity of crashes. Models predicting accidents for rural and urban roads are provided in this manual, including as the accident unit costs per VMT. Changes in accident costs are calculated using Equation C-1 (AASHTO 2010):

$$\Delta AC_C = \upsilon_I \Delta I + \upsilon_D \Delta D + \upsilon_P \Delta P \qquad \text{C-1}$$

Where:
ΔAC_c = change in accident cost (cents/vehicle-mile) for vehicle class *c*
ΔI = change in expected number of injury accidents per vehicle-mile
ΔD = change in expected number of fatal accidents per vehicle-mile
ΔP = change in number of property-damage accidents per vehicle-mile
υ_I = perceived cost associated with an injury accident (cents)
υ_D = perceived cost associated with a fatal accident (cents)
υ_P = perceived cost associated with a property-damage accident (cents)

Mobility: Mobility performance measures are related to the traffic flow and time spent on the highway. Consequences due to delayed maintenance are associated with increased congestion and travel costs. Delaying maintenance treatments may result in more time-consuming and labor-intensive treatments in the future. Application of a rehabilitation or reconstruction typically causes more congestion and travel delays on a section compared to a preventive maintenance treatment. Figure C-14 shows an example with mock-up data of average hours spent per year per traveler due to a delayed maintenance scenario.

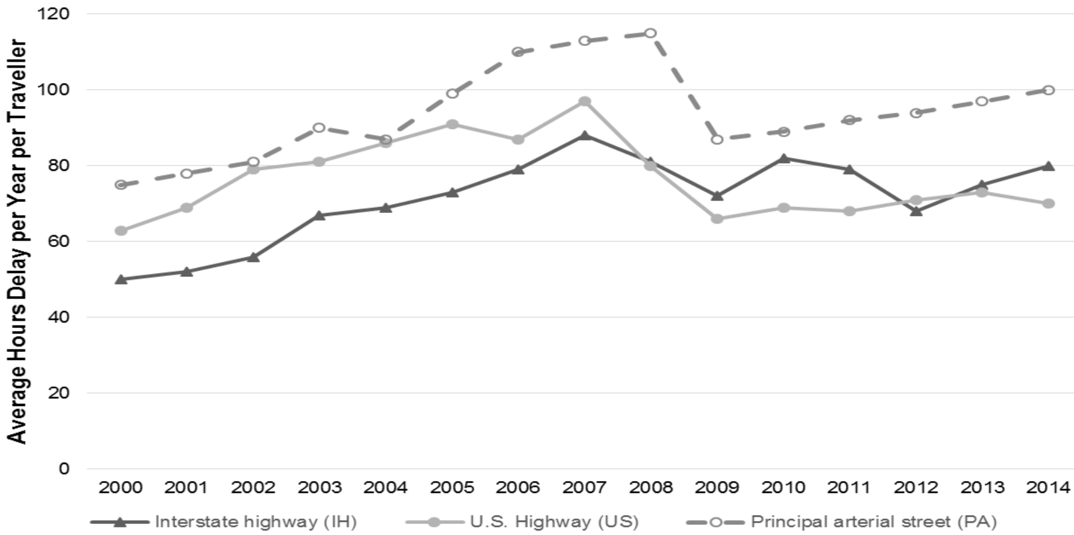


Figure C-14. Average hours delayed per year per traveler due to delayed maintenance.

Users' costs can be estimated based on travel time since delaying of maintenance treatments is likely to cause larger disruptions and closures due to rehabilitation and replacement activities. The value of travel-time savings can be calculated using Equation C-2 (AASHTO 2010):

$$\Delta H_C = 100 M_C O_C \left(\frac{1}{S_0} - \frac{1}{S_1}\right) \qquad \textit{C-2}$$

Where:
ΔH_C = the value of travel-time savings by user class *c* (cents per vehicle-mile)
M_c = the unit value of time for user class *c* (dollars per hour)
O_c = the occupancy rate of vehicles of user class c
S_0, S_1 = the speed without (S_0) and with (S_1) the improvement (miles per hour)

At the project level, there are analytical tools recommended by FHWA to calculate travel delay costs (e.g., Real Cost, MicroBENCOST). For example, RealCost estimates the user costs associated with time delayed in a work zone operation based on the value of user's time for passenger cars, single unit trucks, and combination trucks; and the length, duration, vehicular capacity, speed limit of the traffic at the work zone (FHWA 2004). MicroBENCOST estimates the travel costs based on the days a work zone is in place, the number of lanes affected, and the capacity per lane per hour during the closure (Mallela and Sadasivam 2011).

Environmental: Performance measures include pollutant emissions as well as amount of hazardous waste (Zietsman et al. 2006). There are several sources to obtain the pollutant emission factors, including the U.S. Environmental Protection Agency, Intergovernmental Panel on Climate Change, and European Monitoring and Evaluation Program.

In transportation, gas emissions are typically associated to fuel consumption. Fuel consumption in ml/km is converted to mpg to calculate the gas emissions using the following procedure (GHG 2005):

Fuel used = fuel consumption * distance *C-3*

CO_2 and NO_2 emissions = fuel used * emission factor *C-4*

Although, there are many factors affecting fuel consumption and gas emissions as rolling resistance, internal friction, and air drag; pavement condition is commonly used. As the pavement condition deteriorates due to delayed maintenance, the pavement roughness increases. A research study was conducted in Texas to determine a relationship between the pavement condition, in terms of IRI and vehicle gas emissions. The general equation for gas emissions based on IRI is given by (Chang et al., 2016):

$$\text{Vehicle Gas Emissions (g/mile)} = \text{m. IRI (in/mile)} + \text{b} \qquad \textit{C-5}$$

Table C-6 shows the equation parameters to estimate gas emissions for CO_2, CO, HC and NO_x based on IRI.

Table C-6. Regression analysis results for IRI-Gas emissions.

PEMS – Gas Y (g/mile)	m	b	R^2
CO_2	1.1074	278.89	0.5085
CO	0.0023	0.5577	0.5626
HC	0.0004	0.0644	0.4626
NO_x	0.0003	0.1039	0.2691

Note: Y (Gas g/mile) = m IRI (in/mile) + b

A relationship between IRI and fuel consumption is found in NCHRP Report 720 (Chatti and Zaabar 2012). Table C-7 shows the effect of roughness on fuel consumption for different type of vehicles. It is observed that fuel consumption is higher at lower speeds (35 mph [56 km/h]) than fuel consumption at higher speeds (70 mph [113 km/h]).

The user's fuel costs are obtained using Equation C-6 (AASHTO 2010):

$$C_{fuel} = 100E_{gmp}P_{fuel} \qquad \textit{C-6}$$

Where:
C_{fuel} = user cost of fuel
E_{mp} = fuel efficiency, in gallons per mile
P_{fuel} = fuel price, in dollars per gallon

At the network level, the impact of delayed maintenance can be expressed by gas emissions and user's costs as previously explained but also in social costs. Figure C-15 shows a generic example of the pavement network condition and CO_2 emissions for a delayed maintenance scenario. The CO_2 emissions can be converted to social costs as described by the US Environment and Protection Agency (EPA), which "includes (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (IWGSCC 2013). Table C-8 shows the social cost of CO in dollars per vehicle-mi.

Table C-7. Effect of roughness on fuel consumption.

Speed	Vehicle Class	Calibrated HDM 4 Model					
		Base Fuel Consumption (mL/km)	Adjustment factors from the base value				
		IRI (m/km)					
		1	2	3	4	5	6
56 km/h (35mph)	Medium car	70.14	1.03	1.05	1.08	1.10	1.13
	Van	76.99	1.01	1.02	1.03	1.04	1.05
	SUV	78.69	1.02	1.05	1.07	1.09	1.12
	Light truck	124.21	1.01	1.02	1.04	1.05	1.06
	Articulated truck	273.41	1.02	1.04	1.07	1.09	1.11
88 km/h (55mph)	Medium car	83.38	1.03	1.05	1.08	1.10	1.13
	Van	96.98	1.01	1.02	1.03	1.04	1.05
	SUV	101.29	1.02	1.04	1.07	1.09	1.11
	Light truck	180.18	1.01	1.02	1.03	1.04	1.05
	Articulated truck	447.31	1.02	1.03	1.05	1.06	1.08
112 km/h (70mph)	Medium car	107.85	1.02	1.05	1.07	1.09	1.12
	Van	128.96	1.01	1.02	1.03	1.03	1.04
	SUV	140.49	1.02	1.04	1.06	1.08	1.10
	Light truck	251.41	1.01	1.02	1.02	1.03	1.04
	Articulated truck	656.11	1.01	1.02	1.04	1.05	1.06

* mpg = 2352 / (mL/km)

Source: Chatti and Zaabar 2012

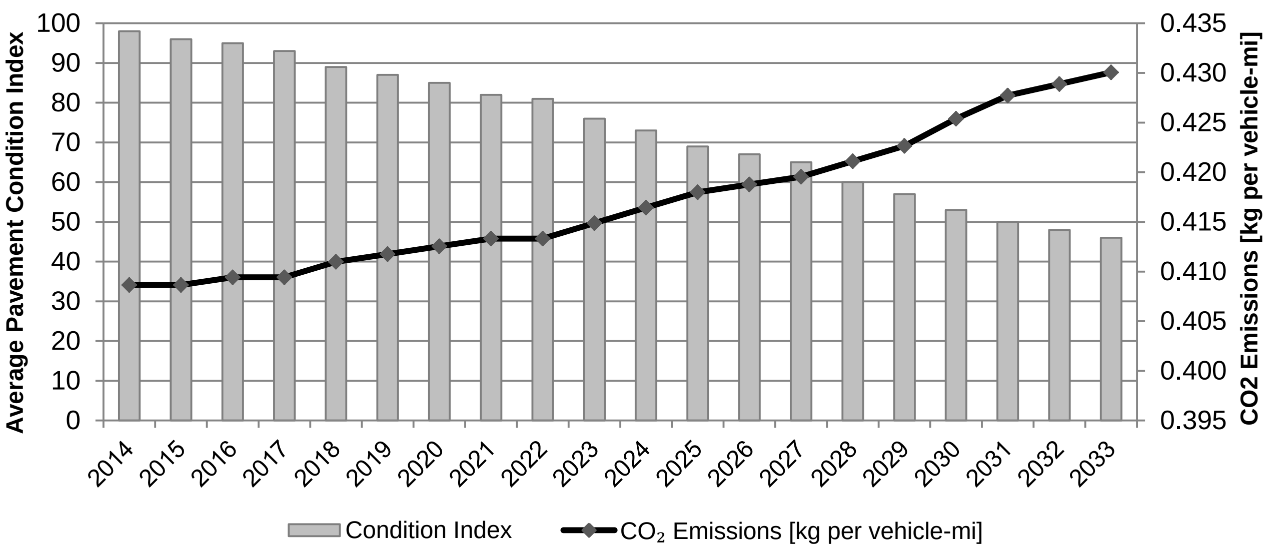


Figure C-15. Projection of pavement network condition and gas emissions.

Table C-8. Environmental and social costs of CO_2.

Year	Condition Index	CO_2 Emissions [kg per vehicle-mi]	Social Cost of CO_2 [$ per kg, 3 percent discount rate]	Social Cost of CO_2 in a given year [$ per vehicle-mi]
2014	98	0.409	0.033	0.013
2015	96	0.409	0.038	0.016
2016	95	0.409	0.038	0.016
2017	93	0.409	0.038	0.016
2018	89	0.411	0.038	0.016
2019	87	0.412	0.038	0.016
2020	85	0.413	0.043	0.018
2021	82	0.413	0.043	0.018
2022	81	0.413	0.043	0.018
2023	76	0.415	0.043	0.018
2024	73	0.416	0.043	0.018
2025	69	0.418	0.048	0.020
2026	67	0.419	0.048	0.020
2027	65	0.420	0.048	0.020
2028	60	0.421	0.048	0.020
2029	57	0.423	0.048	0.020
2030	53	0.425	0.052	0.022
2031	50	0.428	0.052	0.022
2032	48	0.429	0.052	0.022
2033	46	0.430	0.052	0.022

Source: IWGSCC 2013

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

The following provides the step-by-step procedure described above. In this example, a pavement management system (PMS) is used to illustrate the application of the procedures. It is considered that agencies have their own PMS already implemented to assist in the development of their maintenance and rehabilitation programs. These PMS incorporate the agency's customized performance measures, models, prioritization methods, and reports.

C.4 Step 1: Define the Pavement Network Preservation Policy

C.4.1 Identify the Types of Maintenance Activities

In this example, preventive maintenance treatments are applied at predefined time intervals and corrective maintenance is based on triggered condition values. Maintenance treatments include crack seals, slurry seals, and microsurfacing. There are also rehabilitation treatments including hot mix asphalt (HMA) overlays of various thicknesses with milling or recycling prior to the overlay.

C.4.2 Establish Performance Objectives for the Pavement Network

A Condition Index (CI) is calculated from individual pavement distresses observed in the field based on distress severity and quantity. The CI ranges from 0 to 100, where 100 is a pavement in very good condition and 0 in very poor condition. Another performance measure used in this example is the remaining life (RL). RL is defined as the time between the current condition and the time when the pavement reaches a CI value of 25 as shown in Figure C-16.

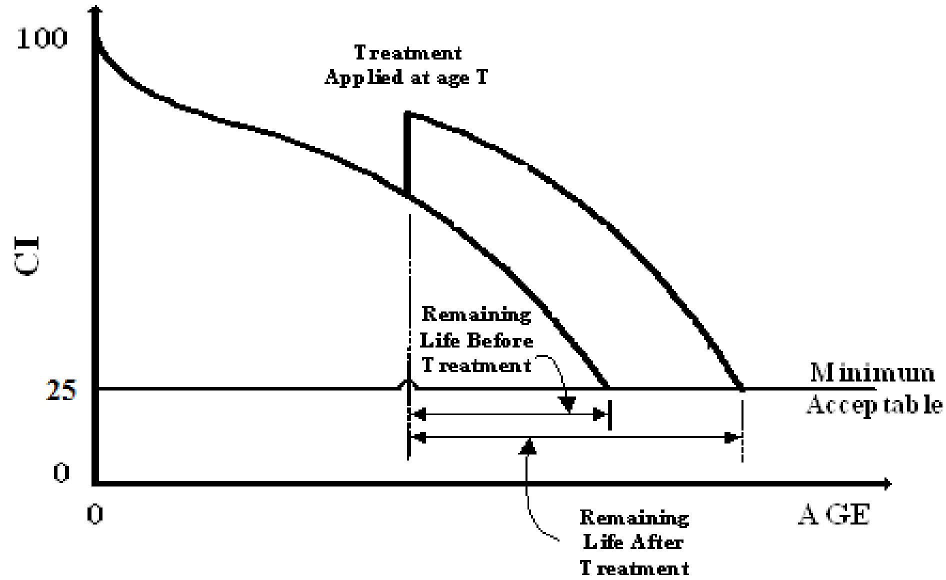
The performance measures for the pavement network in this example include:

- Minimum network average CI = 80
- Minimum network average remaining service life = 25 years
- Minimum percent of the network in good condition = 75 percent
- Maximum percent of the network in poor condition = 10 percent

C.4.3 Formulate Decision Criteria for Pavement Maintenance Activities

The decision criteria are based on predefined time intervals for preventive maintenance and condition triggered for corrective maintenance. Five condition categories are defined in this example based on CI: very good, good, fair, poor, and very poor. The CI breakpoints for each condition category are shown in Table C-9.

A decision tree with a combination of pavement condition categories, functional class, and surface types is used to identify maintenance and rehabilitation treatment needs for each pavement section. A treatment category is assigned to a pavement section based on the condition category using the decision tree shown in Figure C-17.

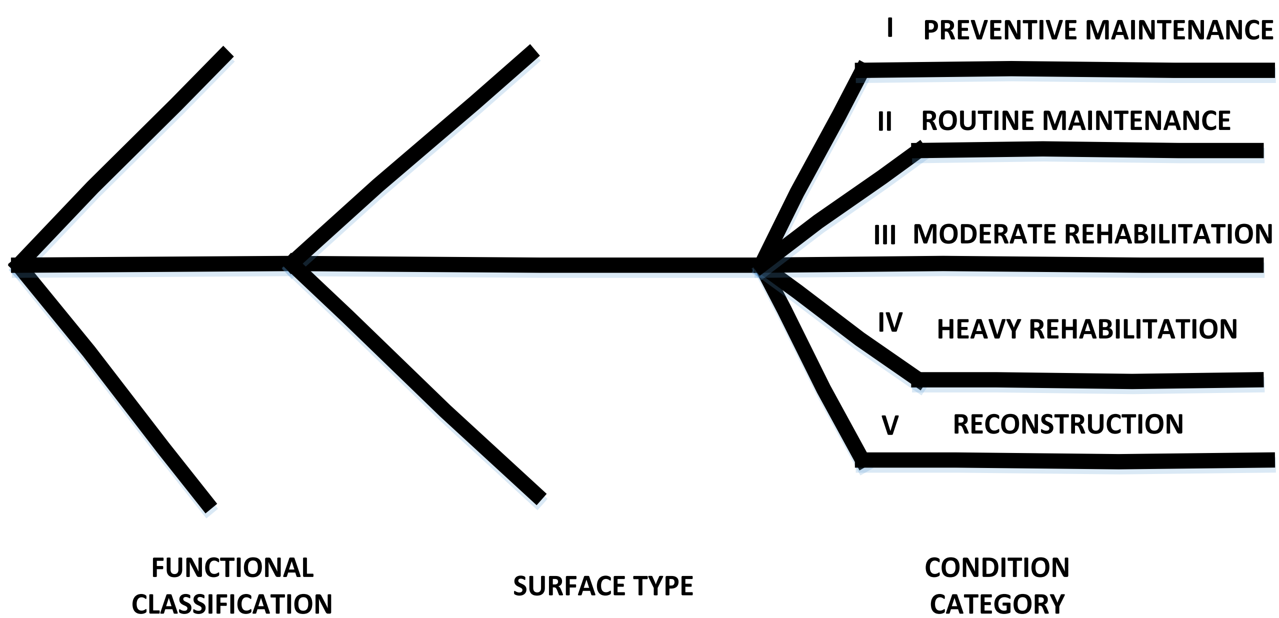


Source: MTC 1988

Figure C-16. Remaining life and minimum acceptable level of service.

Table C-9. CI breakpoints for pavement condition categories.

Category	CI	Condition
I	91-100	Very Good
II	71-90	Good
III	51 - 70	Fair
IV	25-50	Poor
V	Under 25	Very Poor



Source: MTC 1988

Figure C-17. Decision tree to identify treatment needs based on pavement condition.

The treatment intervals for preventive maintenance when the pavement is in very good condition, as well as treatments applied for the other condition categories are shown in Table C-10.

Table C-10. Recommended treatments by condition category.

Treatment Category	Type of Treatment	Timing
	Do nothing	-
I – Preventive maintenance	Microsurfacing	4 years between treatments
	Thin overlay	5 years between treatments
II – Routine maintenance	Thin overlay	based on condition
III – Moderate rehabilitation	Thin overlay	based on condition
IV – Heavy rehabilitation	Thick overlay	based on condition
V – Reconstruction	Reconstruction	based on condition

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

C.5.1 Assess the Pavement Network Condition

Most agencies survey their pavement network with the highest traffic volume (e.g., interstates, primary arterials) every one to two years, and other secondary highways every three to four years. All travel lanes are typically surveyed; parking lanes and paved shoulders may or may not be included. The recommendation is to conduct pavement condition surveys at least once a year for the facilities with the highest priority (i.e. interstate and state highways).

As a reference, for state highway agencies (SHA), the pavement inventory typically includes interstates and primary and secondary state highways. Functional classification is based on the volume and type of traffic, and priority for maintenance. The FHWA classifies the road system into the following categories (FHWA 2013):

- Principal Arterial
  - Interstate
  - Other Freeways & Expressways
  - Other
- Minor Arterial
- Collector
  - Major Collector
  - Minor Collector
- Local

The main surface types for the pavement sections are HMA, Portland cement concrete (PCC), and composite pavements. In this example, the pavement network consists of 693 lane miles and includes principal arterials, minor arterials, and collectors. All pavement sections in this pavement network are HMA. The data elements for each section in the pavement network include:

- Highway or Road ID
- Section ID
- Highway or Road Name
- Begin Location/point
- End Location/point
- Number of Lanes
- Functional Class
- Length, width, area
- Surface Type
- Year Constructed

In this example, it is assumed that the SHA conducts surveys using their own distress protocols. The individual distresses are typically defined by the SHA; however, many have adopted the distress definitions described in the FHWA LTPP *Distress Identification Manual* (Miller and Bellinger 2014). The distress types described by LTPP for HMA pavements include:

- Fatigue cracking
- Block cracking
- Edge cracking
- Longitudinal cracking
- Reflection cracking at joints
- Transverse cracking
- Patch deterioration
- Potholes
- Rutting
- Shoving
- Bleeding
- Polished aggregate
- Raveling
- Lane-to-shoulder drop-off
- Water bleeding and pumping

Figure C-18 shows an LTPP distress summary form.

Another distress protocol commonly used is ASTM D6433-11, *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. The flexible pavement distress types include:

- Alligator cracking
- Bleeding
- Block cracking
- Bumps and sags
- Corrugation
- Depression
- Edge cracking
- Reflection cracking
- Lane-to-shoulder drop-off
- Long & trans cracking
- Patching & utility cut patching
- Polished aggregate
- Potholes
- Railroad crossing
- Rutting
- Shoving
- Slippage cracking
- Swell
- Weathering & raveling

Revised Dec 1992; Jan 1999; Feb 2002; Jul 2010

SHEET 1

DISTRESS SURVEY

LTPP PROGRAM

STATE CODE __ __

SHRP SECTION ID __ __ __ __

DISTRESS SURVEY FOR PAVEMENTS WITH ASPHALT CONCRETE SURFACES

DATE OF DISTRESS SURVEY (MONTH/DAY/YEAR) __ __, __ __, __ __

SURVEYORS: __ __ __, __ __ __ PHOTOS, VIDEO, OR BOTH WITH SURVEY(P,V,B) __
PAVEMENT SURFACE TEMP - BEFORE __ __ __ __°C; AFTER __ __ __ __°C

DISTRESS TYPE	SEVERITY LEVEL LOW	MODERATE	HIGH
CRACKING			
1. FATIGUE CRACKING (SQUARE METERS)	__ __ __.__	__ __ __.__	__ __ __.__
2. BLOCK CRACKING (SQUARE METERS)	__ __ __.__	__ __ __.__	__ __ __.__
3. EDGE CRACKING (METERS)	__ __ __.__	__ __ __.__	__ __ __.__
4. LONGITUDINAL CRACKING			
4a.Wheelpath (Meters)	__ __ __.__	__ __ __.__	__ __ __.__
Length Sealed (Meters)	__ __ __.__	__ __ __.__	__ __ __.__
4b.Non-Wheelpath(Meters)	__ __ __.__	__ __ __.__	__ __ __.__
Length Sealed (Meters)	__ __ __.__	__ __ __.__	__ __ __.__
5. REFLECTION CRACKING AT JOINTS	Not Recorded		
6. TRANSVERSE CRACKING Number of Cracks	__ __ __	__ __ __	__ __ __
Length (Meters)	__ __ __.__	__ __ __.__	__ __ __.__
Length Sealed	__ __ __.__	__ __ __.__	__ __ __.__
PATCHING AND POTHOLES			
7. PATCH/ PATCH DETERIORATION (Number)	__ __ __	__ __ __	__ __ __
(Square Meters)	__ __ __.__	__ __ __.__	__ __ __.__
8. POTHOLES (Number)	__ __ __	__ __ __	__ __ __
(Square Meters)	__ __.__ __	__ __.__ __	__ __.__ __

Source: Miller and Bellinger 2014

Figure C-18. LTPP distress summary form for asphalt concrete surfaces.

Revised April 23, 1993; September 1998; June 1999

SHEET 2

DISTRESS SURVEY

LTPP PROGRAM

STATE CODE __ __

SHRP ID __ __ __ __

DATE OF DISTRESS SURVEY(MONTH/DAY/YEAR) __ __/ __ __/ __ __

SURVEYORS: __ __ __/ __ __ __

DISTRESS SURVEY FOR PAVEMENTS WITH ASPHALT CONCRETE SURFACES
(CONTINUED)

DISTRESS TYPE	SEVERITY LEVEL LOW	SEVERITY LEVEL MODERATE	SEVERITY LEVEL HIGH
SURFACE DEFORMATION			
9. RUTTING - REFER TO SHEET 3 FOR SPS - 3 FOR FORM S1 SEE DIPSTICK MANUAL			
10. SHOVING			
(Number)			__ __ __
(Square Meters)			__ __ __.__
SURFACE DEFECTS			
11. BLEEDING			
(Square Meters)			__ __ __.__
12. POLISHED AGGREGATE			
(Square Meters)			__ __ __.__
13. RAVELING			
(Square Meters)			__ __ __.__
MISCELLANEOUS DISTRESSES			
14. LANE-TO-SHOULDER DROPOFF - NOT RECORDED			
15. WATER BLEEDING AND PUMPING			
(Number)			__ __ __
Length of Affected Pavement (Meters)			__ __ __.__
16. OTHER (Describe)			

Source: Miller and Bellinger 2014

Figure C-18. LTPP distress summary form. (Continued)

In this example, a pavement network with an average CI of 65, which is considered to be in fair condition, is used to illustrate the procedure to quantify the consequences of delayed maintenance. Figure C-19 shows the current pavement network condition. As shown in Figure C-19, at the beginning of the analysis period 15 percent of the pavement network is in poor (12.8 percent) or very poor (2.2 percent) condition, 35.6 percent in fair condition, and 49.5 percent is in good (47.8 percent) or very good (1.7 percent) condition.

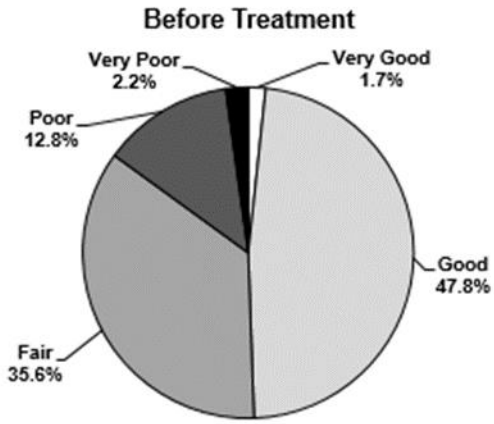


Figure C-19. Pavement network current condition.

C.5.2 Select Performance Models to Forecast the Pavement Network Condition

CI family performance curves that relate age to condition for different combinations of functional class and pavement types are used in this example. Figure C-20 shows the family pavement performance curves for major arterials with different surface types.

C.5.3 Perform the Needs Analysis

The needs analysis is conducted using the criteria in the maintenance and rehabilitation decision tree (see Step C.1.3), and the family performance curves (Figure C-20) to predict the CI over time. The needs analysis determines the treatments and budget required to implement the desired preservation policy. The total agency costs and backlog (maintenance and rehabilitation treatments that are needed, but not scheduled due to funding limitations) costs are tallied and reported along with the CI over the entire analysis period. The condition of each pavement section, evaluated each year over the analysis period, determines the appropriate maintenance and rehabilitation treatment and cost based on the decision tree. Since it is less expensive to maintain pavements in good condition rather than poor condition, the needs analysis includes improving pavement sections into very good condition; thereby, prioritizing pavement sections in poor or very poor condition prior to those in good or better condition. Maintenance and rehabilitation projects are selected based on prioritizing those treatments identified as the most cost-effective. Major rehabilitation treatments are applied only as funds are available.

The needs analysis includes an estimate of total agency costs for applying maintenance and rehabilitation costs, the backlog of costs for treatments not applied due to funding constraints, and the percent of pavements in very poor condition at the end of the analysis period.

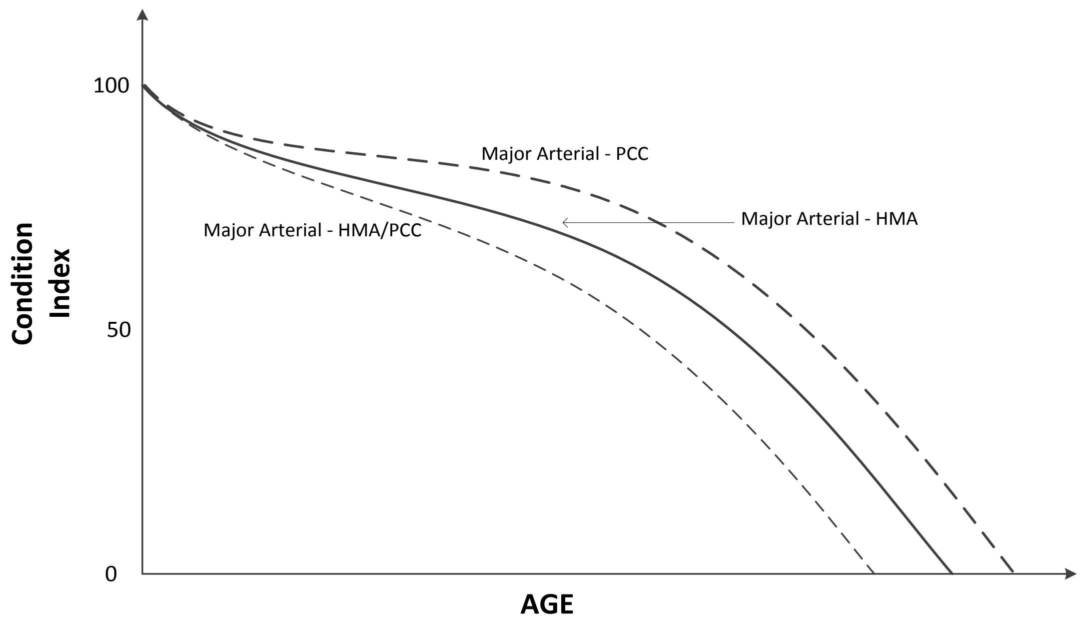


Figure C-20. Example of family pavement performance curves for major arterials.

In addition to the decision tree and performance models, the following assumptions are made to perform the needs analysis:

- Length of the analysis period: 20 years
- Treatment costs (see Table C-11)
- Interest rate: 3 percent
- Inflation rate: 3 percent

A 20-year analysis period is recommended since it is typical for many highway agencies. However, the scenarios analyses period can be 5, 10, 20 years or even longer, and it depends on the agency planning period. The general recommendation is to extend the length of the analysis through the first rehabilitation period after the initial design life.

Table C-11. Treatment costs for the needs analysis.

Functional class	Surface	Treatment Category	Treatment	Cost
Arterial	HMA	I	Microsurfacing	$5.00/Sq Yd
Arterial	HMA	II, III	Thin overlay	$31.00/Sq Yd
Arterial	HMA	IV	Thick overlay	$45.00/Sq Yd
Arterial	HMA	V	Reconstruction	$81.00/Sq Yd
Arterial	HMA/HMA	I	Microsurfacing	$5.00/Sq Yd
Arterial	HMA/HMA	II, III	Mill and thin overlay	$33.00/Sq Yd
Arterial	HMA/HMA	IV	Mill and thick overlay	$47.00/Sq Yd
Arterial	HMA/HMA	V	Reconstruction	$81.00/Sq Yd
Collector	HMA	I	Microsurfacing	$5.00/Sq Yd
Collector	HMA	II, III	Thin overlay	$28.00/Sq Yd
Collector	HMA	IV	Thick overlay	$40.00/Sq Yd
Collector	HMA	V	Reconstruction	$60.00/Sq Yd
Collector	HMA/HMA	I	Microsurfacing	$5.00/Sq Yd
Collector	HMA/HMA	II	Thin overlay	$28.00/Sq Yd
Collector	HMA/HMA	III	Mill and thin overlay	$30.00/Sq Yd
Collector	HMA/HMA	V	Mill and thick overlay	$42.00/Sq Yd
Collector	HMA/HMA	V	Reconstruction	$60.00/Sq Yd
Residential/Local	HMA	I	Microsurfacing	$4.00/Sq Yd
Residential/Local	HMA	II, III	Thin overlay	$24.00/Sq Yd
Residential/Local	HMA	IV	Thick overlay	$34.00/Sq Yd
Residential/Local	HMA	V	Reconstruction	$50.00/Sq Yd
Residential/Local	HMA/HMA	I	Microsurfacing	$4.00/Sq Yd
Residential/Local	HMA/HMA	II, III	Mill and fill thin overlay	$28.00/Sq Yd
Residential/Local	HMA/HMA	IV	Mill and fill thick overlay	$36.00/Sq Yd
Residential/Local	HMA/HMA	V	Reconstruction	$50.00/Sq Yd

C.6 Step 3: Conduct Delayed Maintenance Scenarios Analyses

C.6.1 Formulate Delayed Maintenance Scenarios

In this example, the following maintenance scenarios are considered in the analysis:

Scenario 1.a: All needs to preserve the pavement network in very good condition. In this scenario, maintenance and rehabilitation treatments are performed with sufficient funds to address all the needs to improve the pavement network from fair to very good condition, and preserve the pavement network in very good condition over the analysis period. Maintenance and rehabilitation treatments are applied when needed to comply with the preservation policy. The budget estimates from this scenario is considered as the baseline budget.

Scenario 1.b: Preserve the pavement network in the current condition. This scenario is considered to be a more realistic scenario as it may be unfeasible for an agency to have all the funds required to improve the current condition (network CI = 65) to very good condition (CI > 91). The pavement network under this scenario is maintained at the fair condition category (CI = 51 to 70).

Scenario 2: Do nothing. No maintenance, rehabilitation, or reconstruction treatments are performed; although this is an unfeasible scenario, it provides a second baseline to analyze the results of the remaining scenarios.

Scenario 3: Delayed maintenance. In this scenario, maintenance treatments are delayed by 2 years. Therefore, in this scenario the time interval to apply surface seals is 6 years instead of 4 years as in Scenario 1.

Scenario 4: Budget-driven. In this scenario, there are limited funds for maintenance treatments. There are two cases in this scenario:

a. Forty percent of baseline budget, in which the budget needs identified for maintenance in Scenario 1 are reduced to 40 percent.
b. Zero percent of baseline budget, in which no maintenance is applied to the pavement network, and only major rehabilitation treatments and reconstruction activities are allowed.

C.6.2 Perform the Delayed Pavement Maintenance Scenarios Analyses

The six scenarios formulated in Step C.3.1 were performed to analyze the consequences of delayed maintenance. Table C-12 includes the results for each scenario according to the total agency costs for all work performed over the 20-year analysis period, the backlog costs at the end (Year 20) of the analysis period. The percent of pavements in very poor condition is 2.2 percent at the start of the analysis period.

Table C-12. Summary of results for the pavement maintenance scenarios analyses.

Scenario	Description	Total Agency Cost[1,2]	Backlog Cost[1,2]	Percent Pavements in Very Poor Condition[1]
1	a. All Needs	$325 M	$0	0
	b. Preserve current condition	$181 M	$234.2 M	24.5
2	Do Nothing	$0	$593.5 M	45.1
3	Delayed Maintenance by 2 years	$192 M	$209.7 M	18.6
4	Budget-driven with limited funds			
	a. 40 percent of baseline budget for maintenance	$170 M	$274.7 M	34.1
	b. 0 percent of baseline budget for maintenance	$181 M	$310.9 M	35.8

[1] At the end of the analysis period.
[2] Total cost using a 3 percent interest and inflation rate.

Scenario 1.a requires a total agency expenditure of $325M to implement the agency-desired maintenance program and preserve the highway network over the 20-year analysis period.

Scenario 1.b preserves the current network pavement condition at a CI of 65 over the 20-year analysis period, resulting in an agency cost of $181M; however, by the end of analysis period, this scenario will result in a backlog cost of $234.2M and 24.5 percent of pavements are in very poor condition.

Scenario 2 allows the pavement network to deteriorate due to no funding. By the end of the analysis period, almost half of the pavement network (45.1 percent) is in very poor condition. This scenario also results in the highest backlog cost of $593.5M.

Scenario 3 delays maintenance for 2 years and will require an agency expenditure of $192 million, results in a $209.7M backlog cost, and 18.6 percent of the pavement network is in very poor condition.

Scenario 4.a shows the impact of funding only 40 percent of preventive maintenance needs; the scenario results in a backlog cost of $274.7M and 34.1 percent of pavements in very poor condition. Finally, Scenario 4.b illustrates the consequences of not performing pavement maintenance and results in a total annual cost of $181M, a backlog cost of $310.9M, and 35.8 percent of pavements in very poor condition.

In relation to delayed maintenance, Scenario 3 (delaying maintenance by 2 years) results in a higher total agency cost ($192M versus $181M) than Scenario 1.b (preserve current condition) since delaying maintenance causes a higher expenditure of rehabilitation treatments, and slightly lower backlog cost (approximately $24.5M lower) and percent pavements in poor condition (18.6 versus 24.5 percent). Reducing the allowable maintenance budget, in this case down to 40 percent of specified need (Scenario 4.a), results in total agency costs of $11M less than Scenario 1.b, approximately $40M additional backlog costs, and approximately 10 percent more pavements in very poor condition. Lastly, conducting no maintenance treatments (Scenario 4.b) has the same total agency costs as Scenario 1.b; however, results in a higher backlog costs (approximately $70M higher) and approximately 11 percent more pavement in poor condition.

C.6.3 Determine the Impact and Report the Consequences of Delayed Maintenance

The importance of reporting the consequences of delayed maintenance is to justify the effectiveness of a timely treatment, both in monetary values as well as pavement network condition. The results of the scenarios analyses are used to quantify the consequences on:

- Future pavement condition
- Future remaining service life
- Future budget needs
- Asset value and PSR
- Environmental performance measures (gas emissions)

Consequences on the Future Pavement Network Condition

Figure C-21 shows the impacts of delayed maintenance for each scenario on the overall pavement condition over time. Figure C-21 compares the predicted pavement condition for each scenario from 2015 through 2034. The initial pavement condition for all scenarios begins at a CI = 65 (current network condition, based on Figure C-19) and varies over the next 20-years depending on each budget scenario. As expected, Scenario 1.a results in the highest overall pavement condition of all scenarios by the end of the analysis period, followed by Scenario 3, Scenario 1.b, Scenario 4.a, Scenario 4.b, and Scenario 2 with the worst overall network condition. As discussed previously in Table C-12, Figure C-21 shows that Scenario 1.b (preserve current condition) and Scenario 3 (maintenance treatments delayed by 2-years) result in similar network conditions; however, keep in mind that delaying maintenance results in a higher total agency cost ($181M for Scenario 1.b and $192M for Scenario 3).

Changes in the distribution of the pavement condition category by lane miles are reported over the length of the planning period as shown in Figure C-22. Scenario 1.a addresses all pavement needs and removes all pavements in very poor condition by 2021. In comparison, all other scenarios result in a general trend of increased percent pavements in poor condition over the 20-year analysis period.

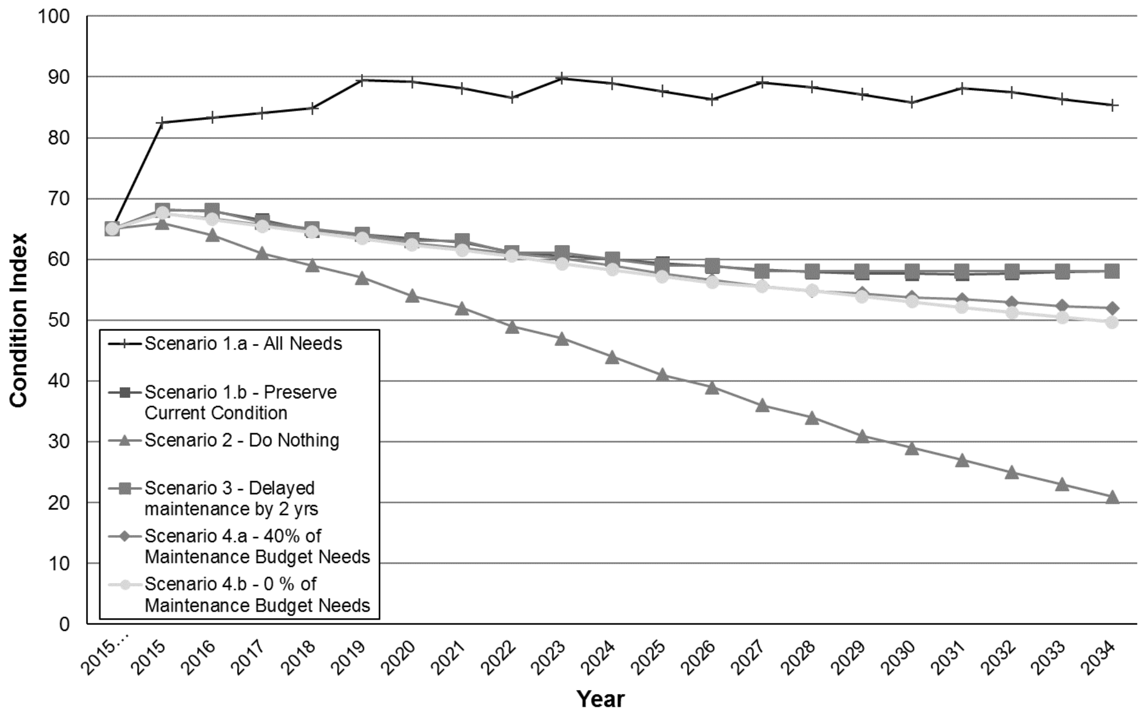


Figure C-21. Impacts of scenario budgets on pavement condition.

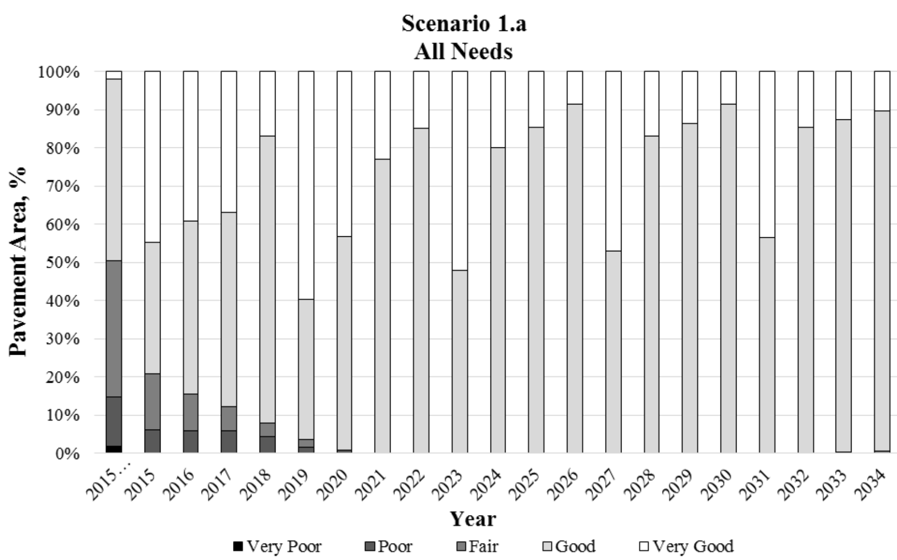
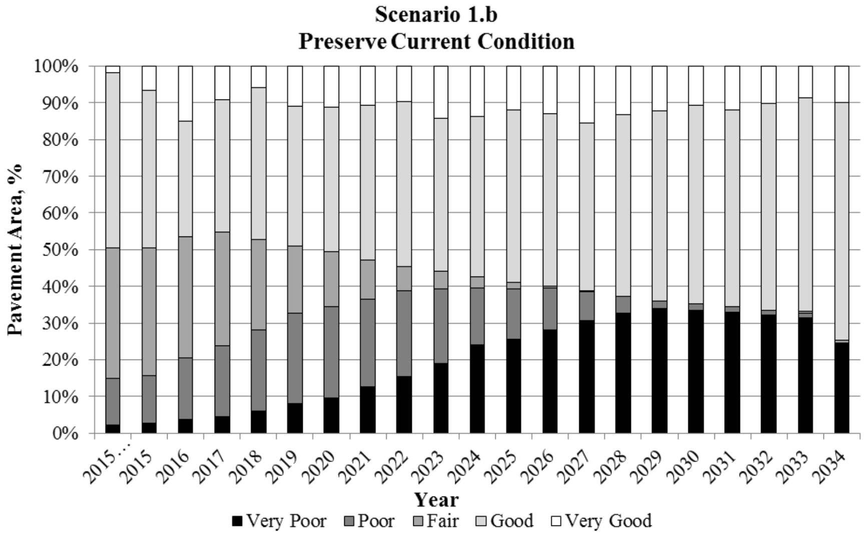
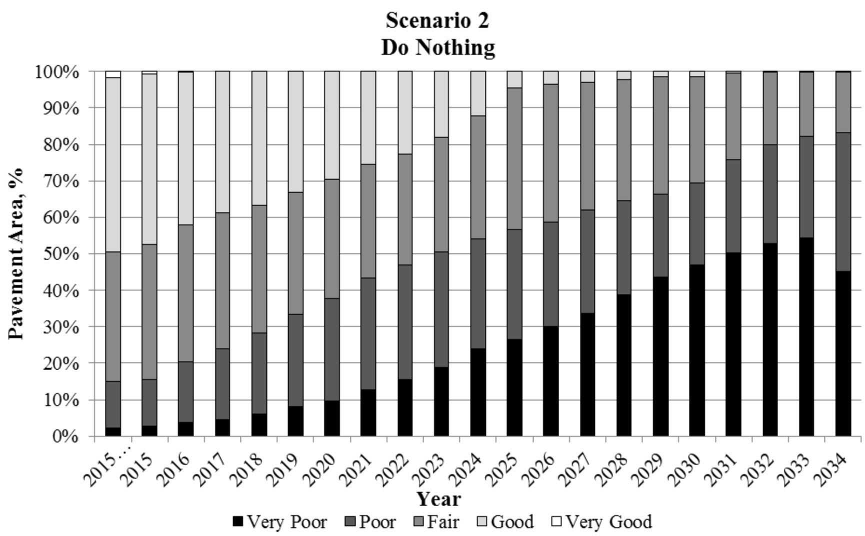


Figure C-22. Pavement area by condition category over time.





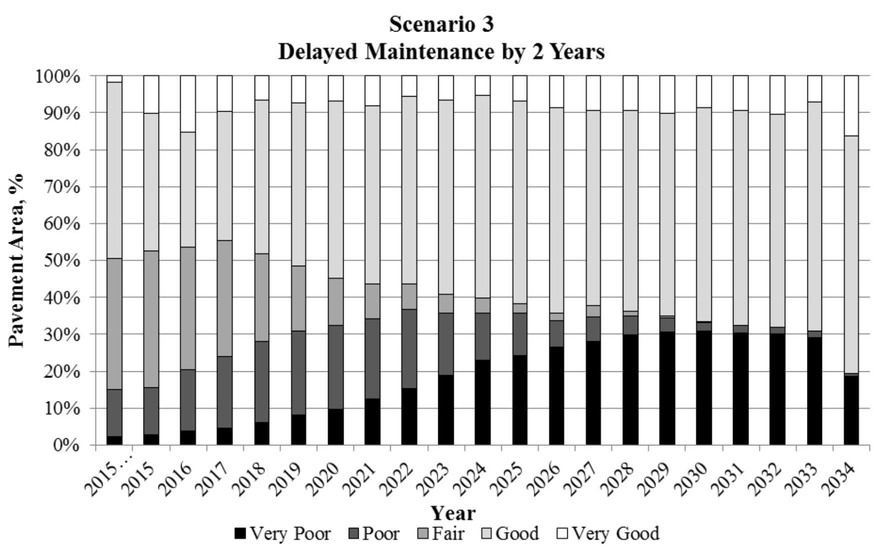
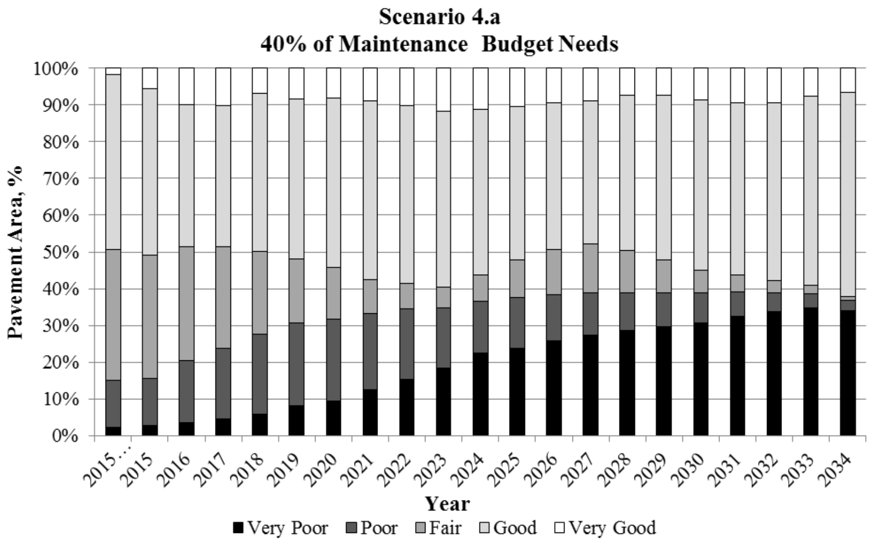


Figure C-22. Pavement area by condition category over time. (Continued)



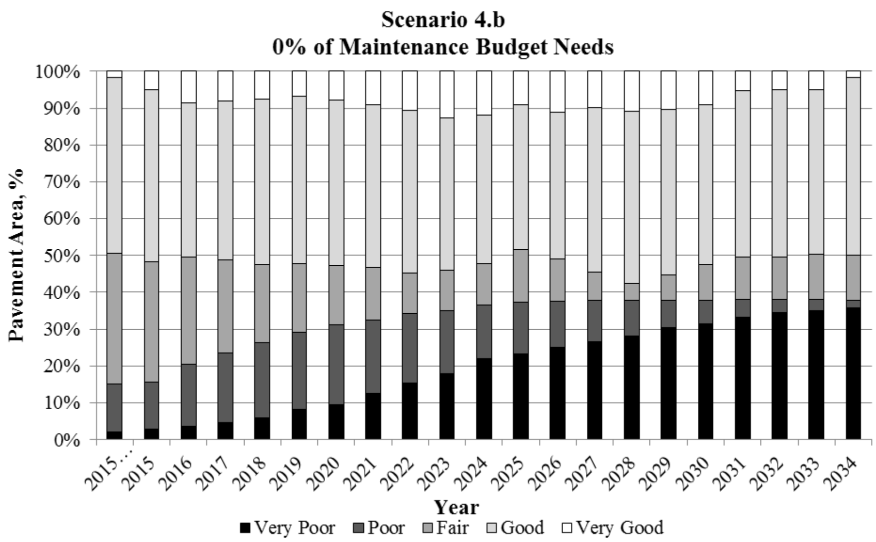


Figure C-22. Pavement area by condition category over time. (Continued)

Figure C-23 illustrates another example of displaying network condition results at the end of the analysis period.

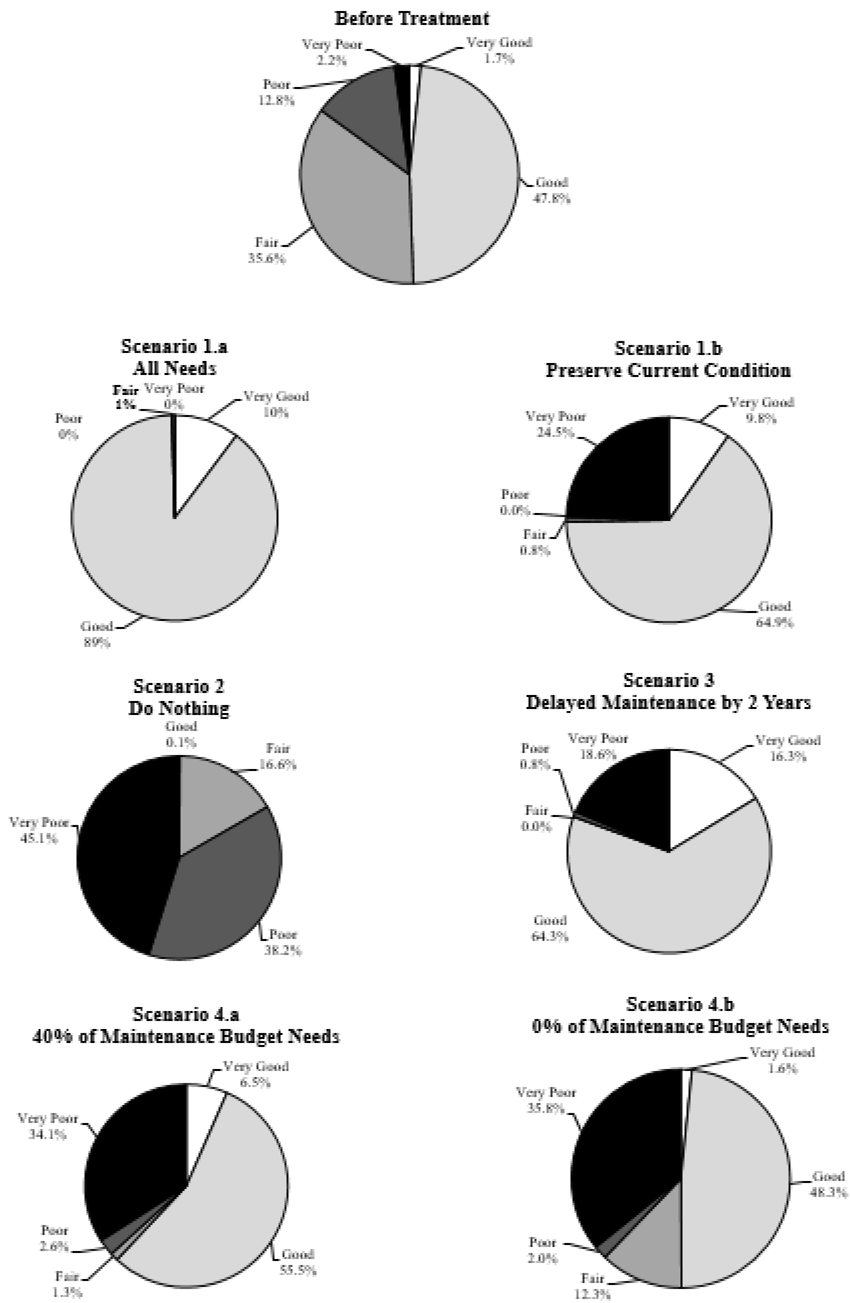


Figure C-23. Pavement network condition at the end of the analysis period, 20 years.

Consequences on the Remaining Service Life of the Pavement Network

The remaining service life is defined as the time from current day to when the pavement reaches an unacceptable condition requiring reconstruction (FHWA 2013). Figure C-24 shows the average pavement network remaining service life (RSL) for each of the six scenarios. Scenario 1.a, all needs, maintains 93 percent of the pavement network with RSL above 20 years, and 7 percent of the network with a RSL above 10 years. Scenario 1.b, preserving the current condition, results in 63 percent with RSL above 20 years and 37 percent of the network with a RSL below 2 years. Scenarios 4.a and 4.b, 40 and 0 percent of baseline budget, show similar remaining lives, where about half of the network has RSL above 20 years but also one third of the network has RSL less than 2 years. Scenario 2, do nothing, results in 62 percent of the pavement network with a RSL below 2 years, 10 percent with a RSL between 2 and 5 years, and 20 percent with RSL between 5 and 10 years.

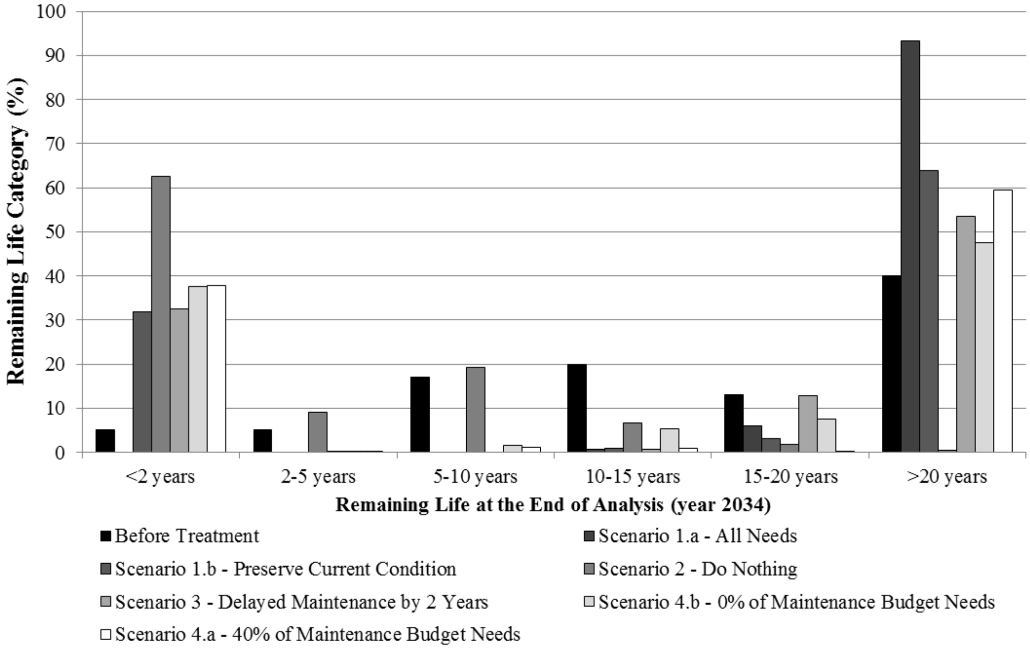
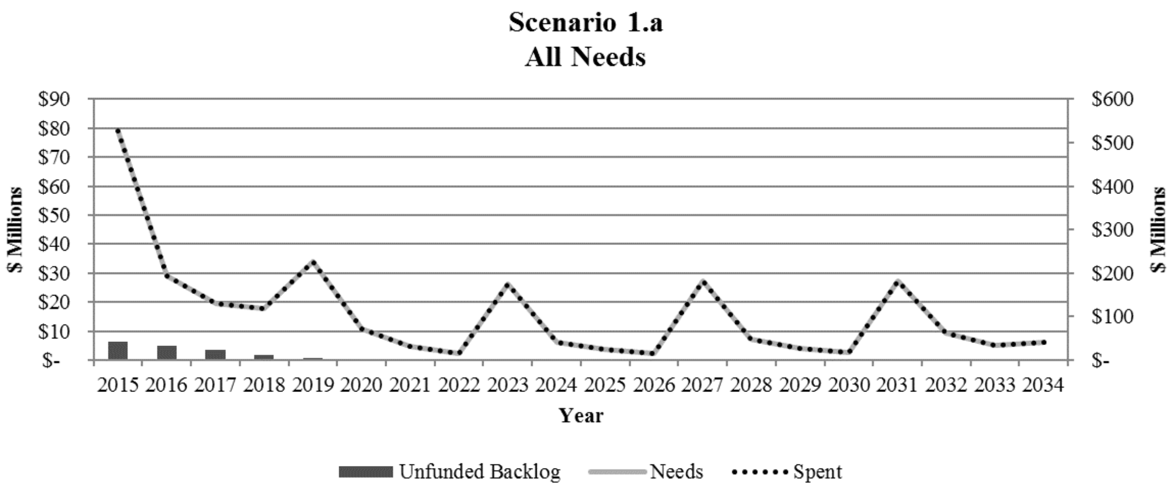
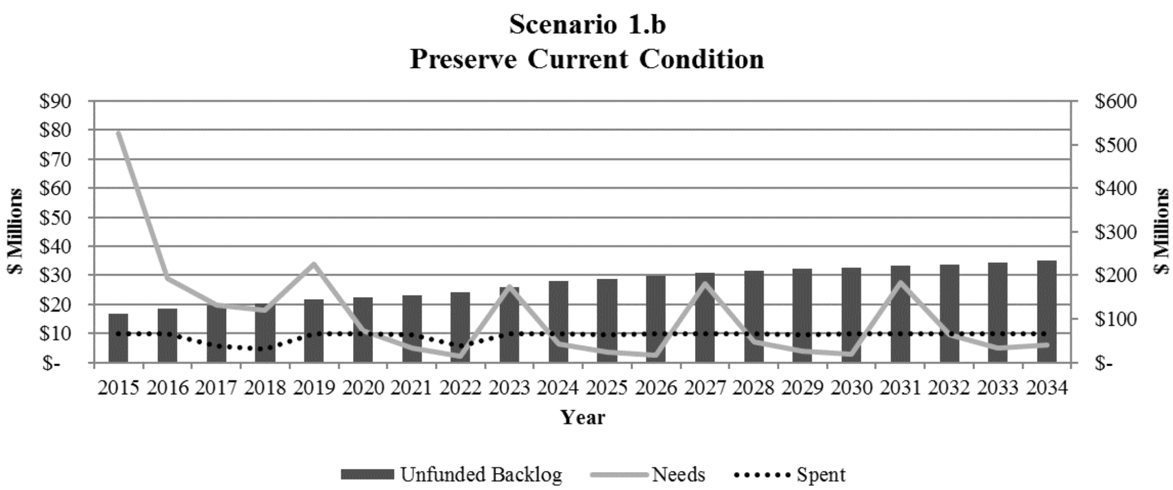


Figure C-24. Remaining Service Life (RSL) at the end of the analysis period.

Consequences on Future Budget Needs

Generally, if maintenance is delayed, more expensive treatments must be applied to restore the pavement to an acceptable condition or level of service at some future date. Funds needed to restore the pavement to the desired condition but not applied are backlogged costs. Backlogged costs are defined by agencies as “the cost to bring all the pavements from their current condition to a state of good repair.” (NYSDOT 2008). Backlogged costs are also defined as the differences in costs between projects that were identified as needed and the projects that were actually funded. (Zimmerman and Peshkin 2006). Backlogged costs are estimated by the difference between needed and allocated funds. Figure C-25 shows the costs for the six scenarios. The highest backlog of $593 million results from Scenario 2, Do Nothing. Scenario 4.a with 40 percent of preventive maintenance needs has slightly lower backlog costs than Scenario 4.b, 0 percent baseline budget. Scenario 3, delayed maintenance by 2 years, has nearly constant backlog costs of $120 million over the period of analysis. Scenario 1.b that preserves the current condition shows a slightly backlog cost increasing trend over time.





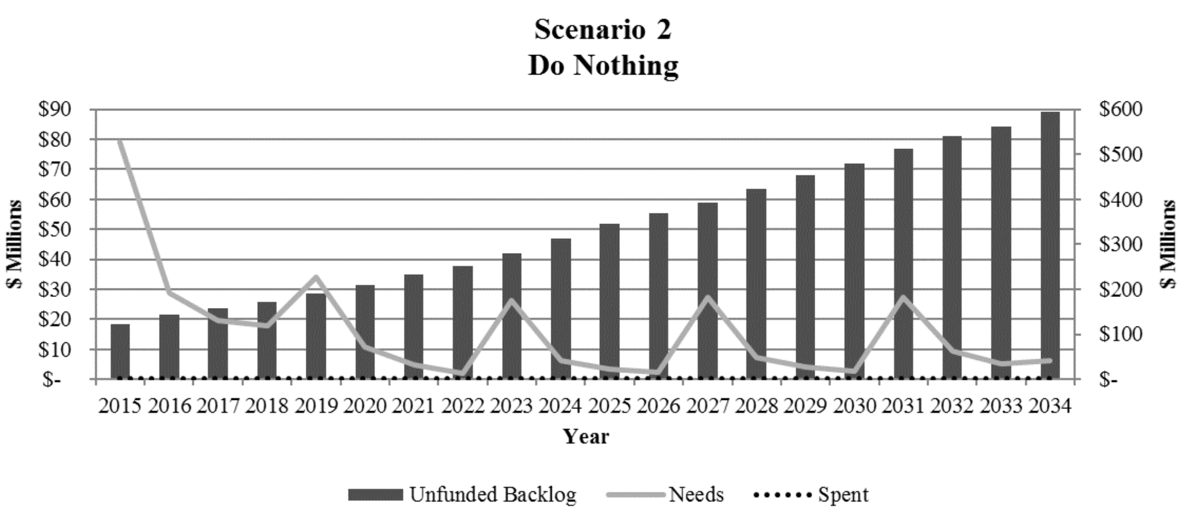
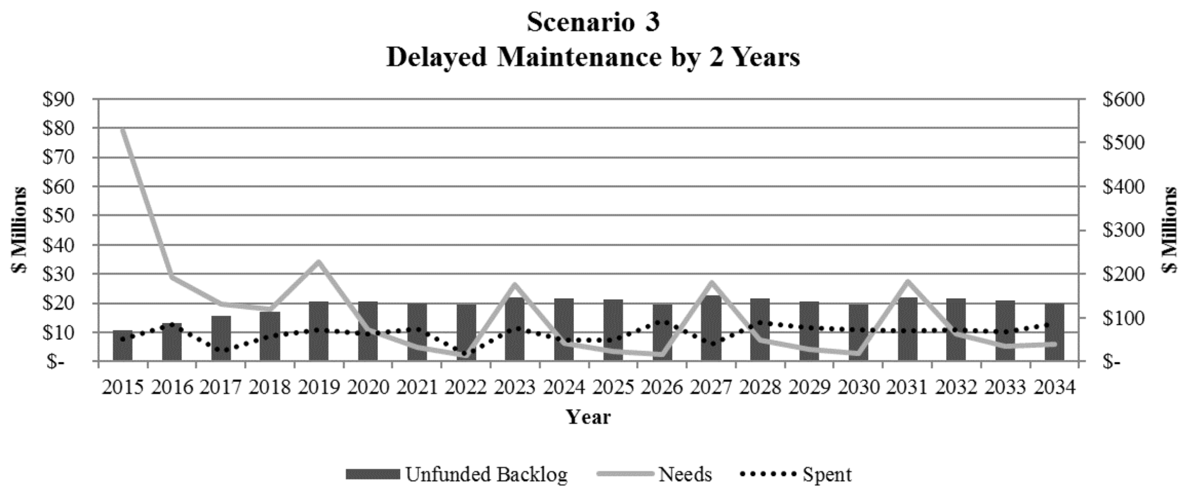
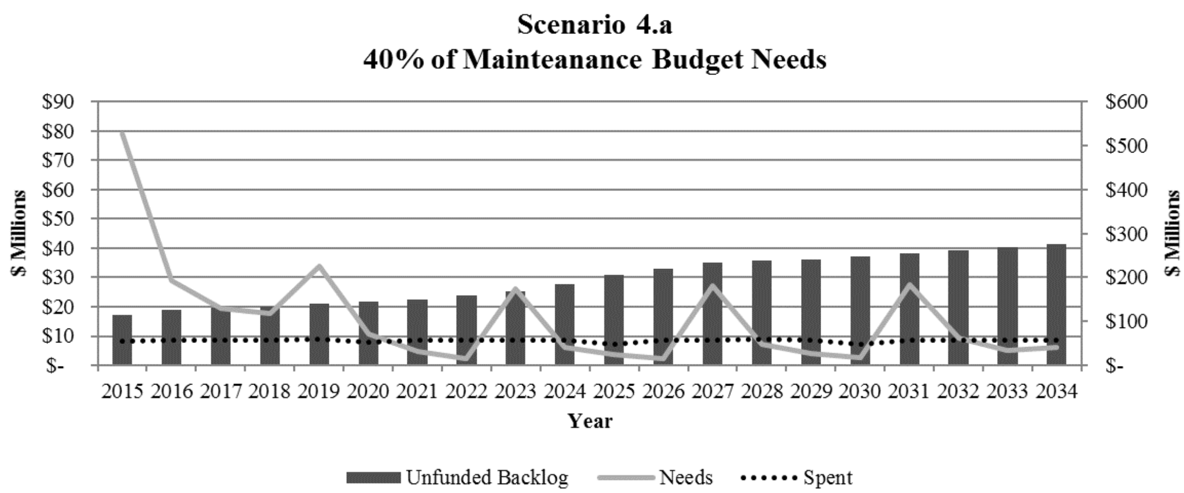


Figure C-25. Funding needs, budget spent, and backlog costs.





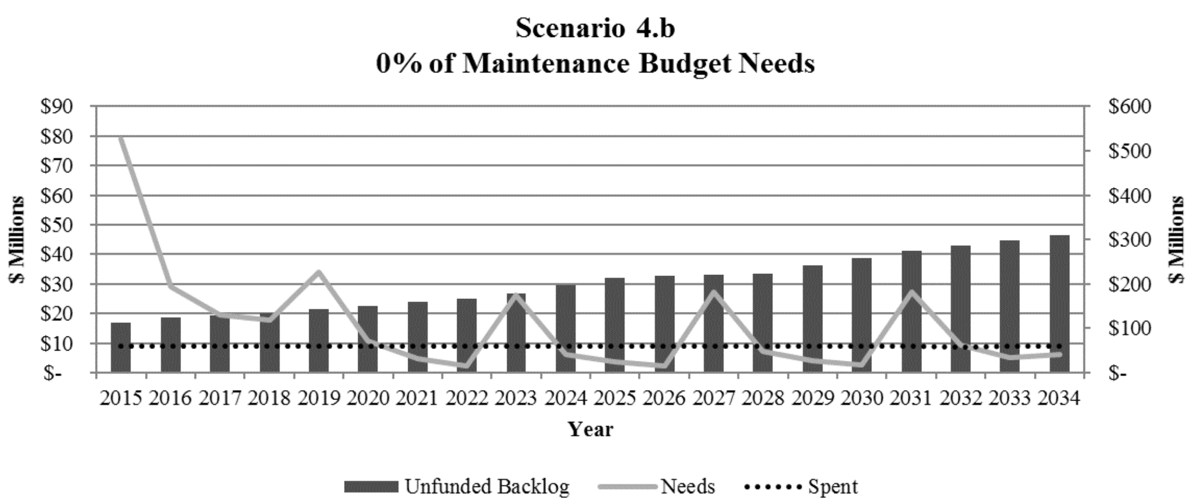
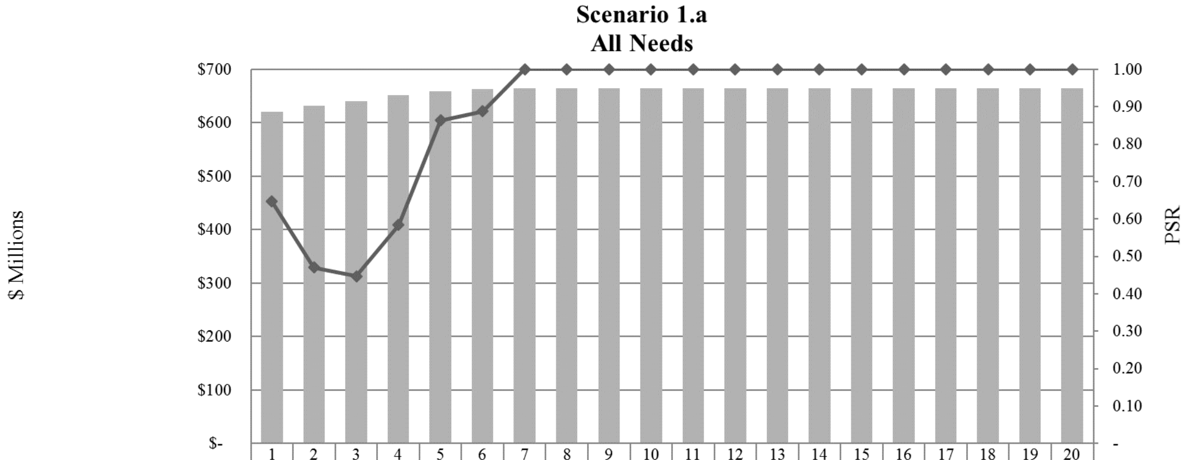


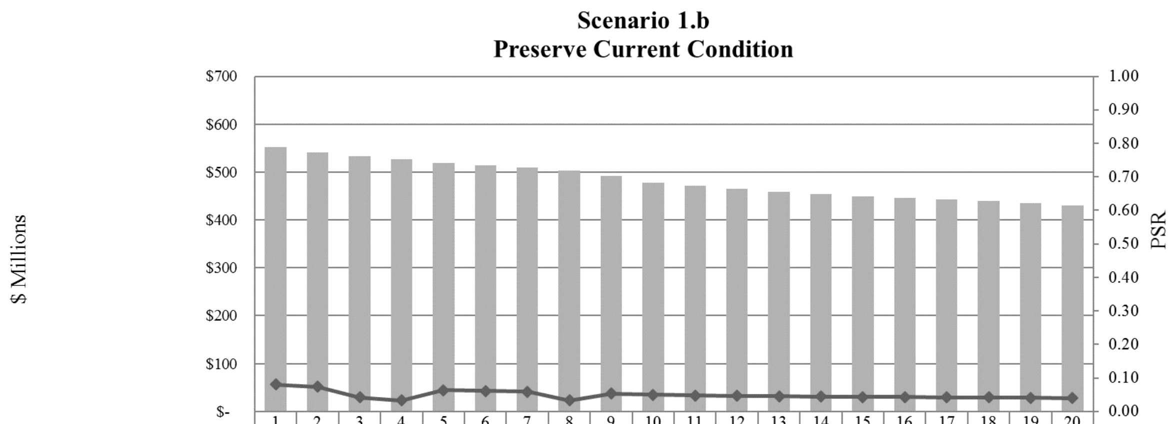
Figure C-25. Funding needs, budget spent, and backlog costs. (Continued)

Consequences on the Pavement Network Value

The asset value of the pavement network together with a Pavement Sustainability Ratio (PSuR) over time is shown in Figure C-26. PSuR is a ratio between the budget spent and pavement network funding needs required to achieve the target condition established by the agency, where a ratio of 1 means that budget spent or allocated funds are equal to the funding needs, ratios below 1 express a decrease of the pavement network value (FHWA 2012).

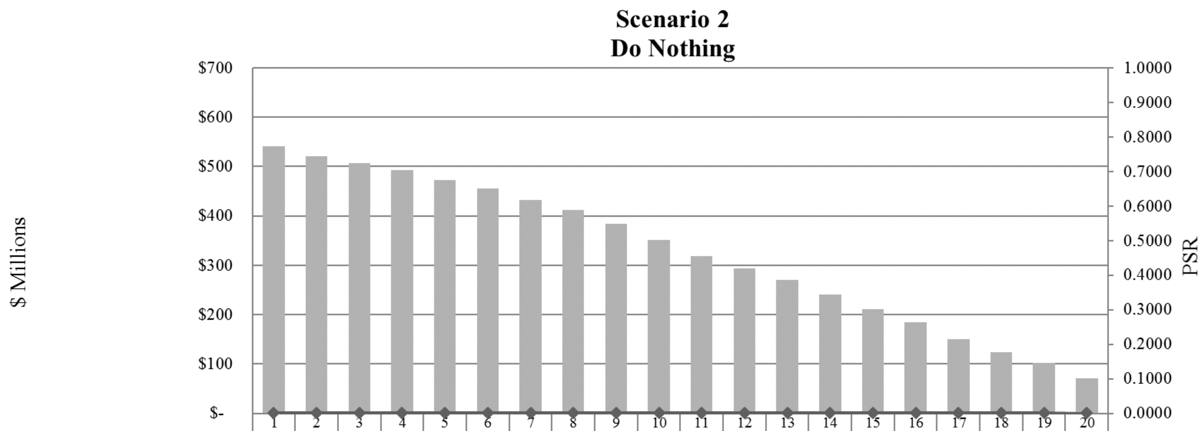


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$621	$631	$640	$651	$658	$662	$664	$664	$664	$664	$664	$664	$664	$664	$664	$664	$664	$664	$664	$664
Sustainability Ratio	0.65	0.47	0.45	0.58	0.86	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

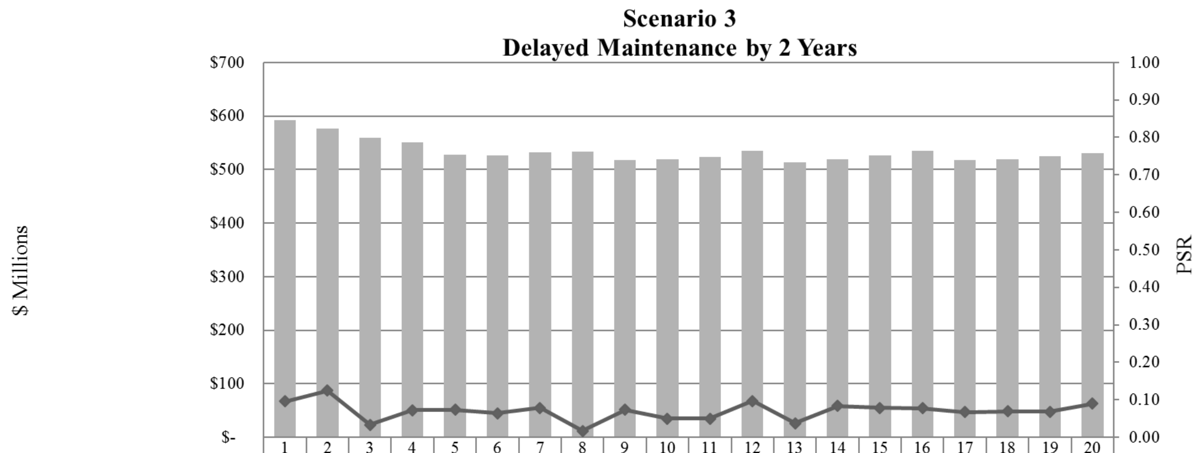


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$55	$54	$53	$52	$51	$51	$51	$50	$49	$47	$47	$46	$45	$45	$44	$44	$44	$43	$43	$43
Sustainability Ratio	0.08	0.07	0.04	0.03	0.06	0.06	0.06	0.03	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04

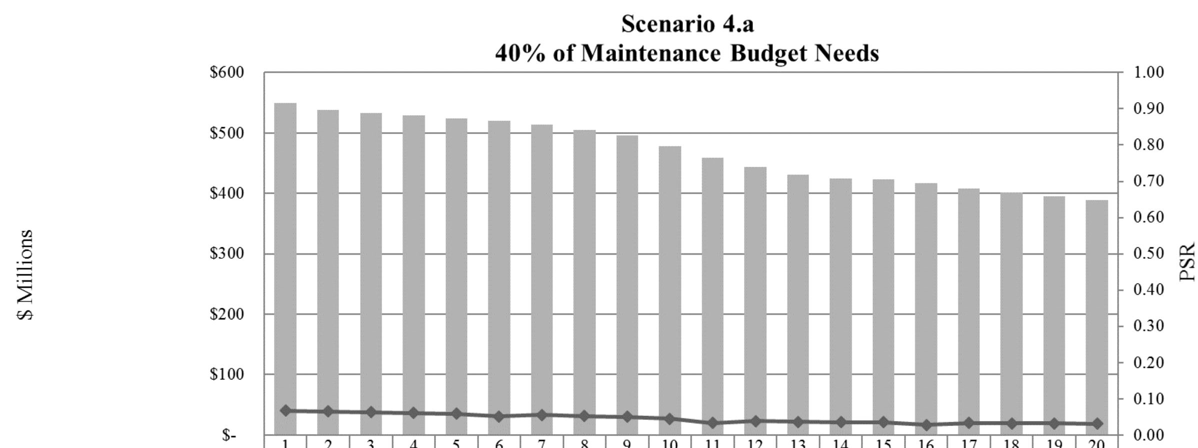
Figure C-26. Pavement network value and pavement sustainability ratio over time.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$542	$521	$506	$492	$473	$456	$432	$412	$384	$351	$318	$294	$271	$241	$211	$185	$151	$124	$102	$70
Sustainability Ratio	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

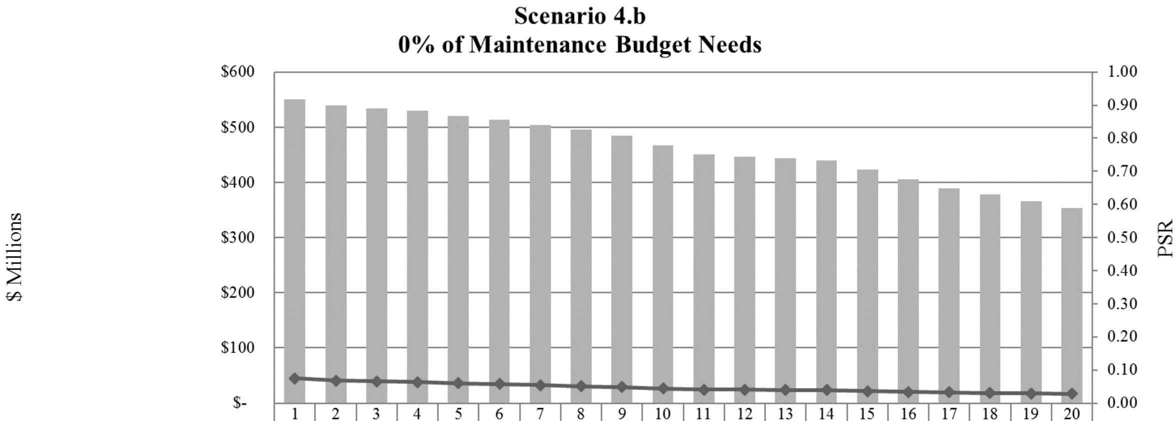


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$59	$57	$56	$55	$52	$52	$53	$53	$51	$51	$52	$53	$51	$51	$52	$53	$51	$51	$52	$53
Sustainability Ratio	0.10	0.12	0.03	0.07	0.07	0.06	0.08	0.02	0.07	0.05	0.05	0.10	0.04	0.08	0.08	0.08	0.07	0.07	0.07	0.09



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$55	$53	$53	$53	$52	$52	$51	$50	$49	$47	$45	$44	$43	$42	$42	$41	$40	$40	$39	$38
Sustainability Ratio	0.07	0.07	0.06	0.06	0.06	0.05	0.06	0.05	0.05	0.04	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03

Figure C-26. Pavement network value and pavement sustainability ratio over time. (Continued)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value (US $ million)	$55	$53	$53	$53	$52	$51	$50	$49	$48	$46	$45	$44	$44	$44	$42	$40	$38	$37	$36	$35
Sustainability Ratio	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03

Figure C-26. Pavement network value and pavement sustainability ratio over time. (Continued)

It is observed that the level of funding impacts the pavement network value. The highest pavement network value is maintained in Scenario 1.a, followed by Scenarios 3 and 1.b. The lowest pavement network value results from Scenarios 2 (no maintenance), and Scenario 4 (treatments conditioned by budget availability).

Consequences on Users' Costs

User costs are influenced by travel-time costs, operating costs, and accident costs. The magnitude of the effect of delayed maintenance on user costs depends primarily on the number of users affected, traffic volume, type of vehicle, and travel speed as described as follows (AASHTO 2010). The analytical tool that was used to prepare this appendix do not have the capabilities to quantify user costs. Please refer to section C.3.3 for additional information on this topic.

Consequences on Environmental Performance

Environmental performance is showed by CO_2 emissions, following the procedure described in section C.3.3. Figure C-27 shows the correlation pavement condition with on-road vehicle CO_2 emissions for all scenarios.

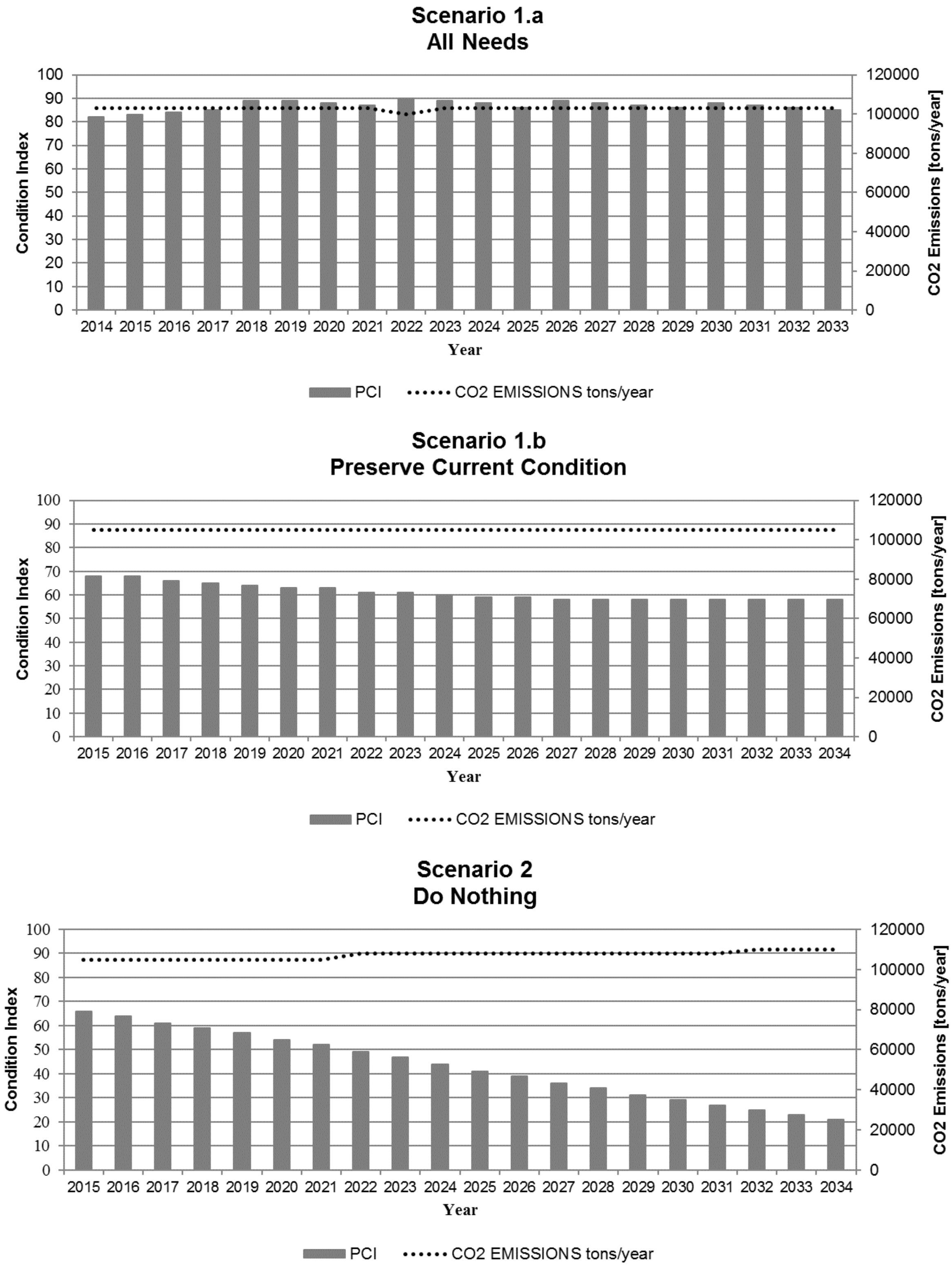
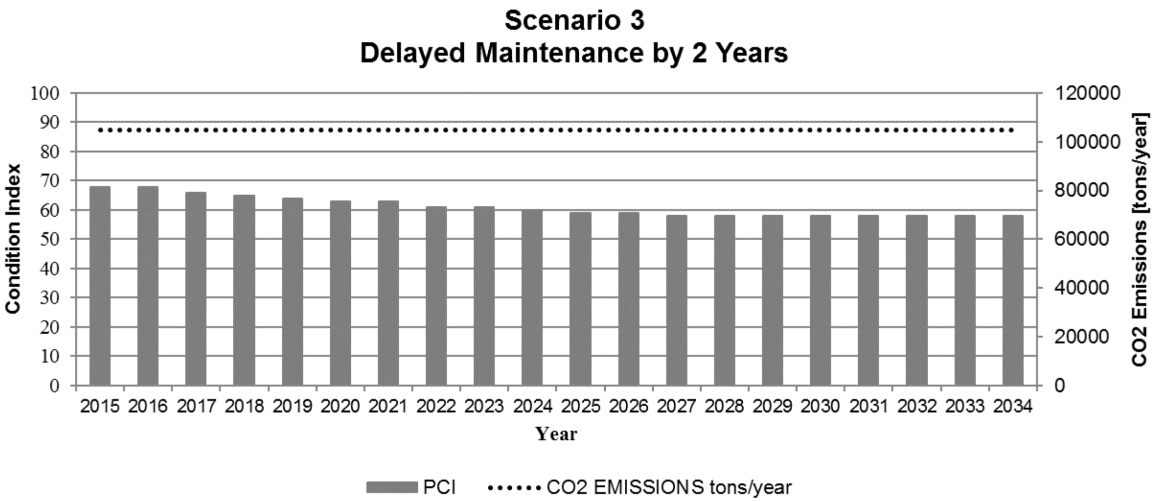
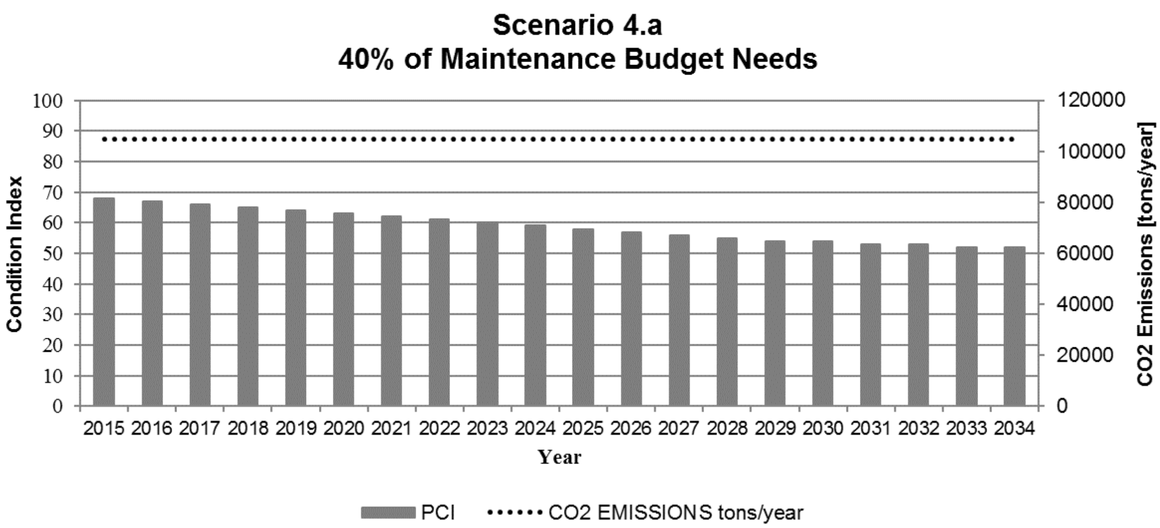


Figure C-27. Pavement network condition and CO_2 emissions over time.





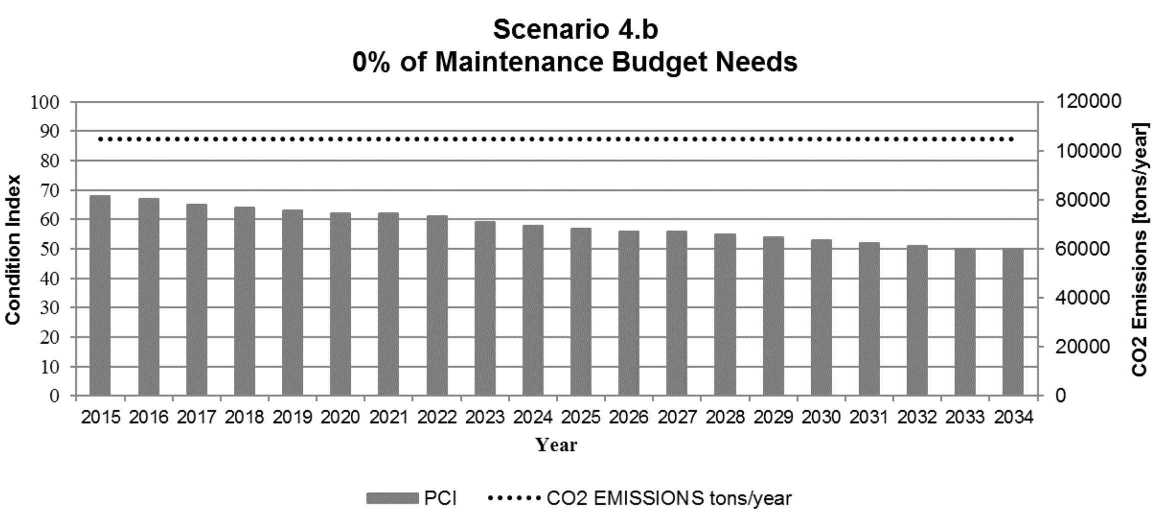


Figure C-27. Pavement network condition and CO_2 emissions over time. (Continued)

The CO_2 emissions are converted to cost using the social cost of carbon recommended by the U.S. EPA, which "includes, but is not limited to, changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (Interagency Working Group on Social Cost of Carbon, United States Government 2013). Figure C-28 shows the social cost of CO_2 compared to the agency maintenance costs. In Scenario 1.a, All Needs, the agency cost of maintenance is \$325 million while social cost of CO_2 is at its lowest, \$93 million. For Scenario 2, Do Nothing, the social cost of CO_2 increases by \$4 million, up to \$97 million. The social cost of CO_2 in Scenarios 1.b, 3, 4.a, and 4.b is the same due to very similar average network CI during the analysis period. It is observed that the social cost of CO_2 emissions amounts to about 2/7 of pavement maintenance costs, even when the highway agency spends enough to meet all needs. On the other hand, social cost of CO_2 emissions rises by less than 5 percent, even if the highway agency spends nothing.

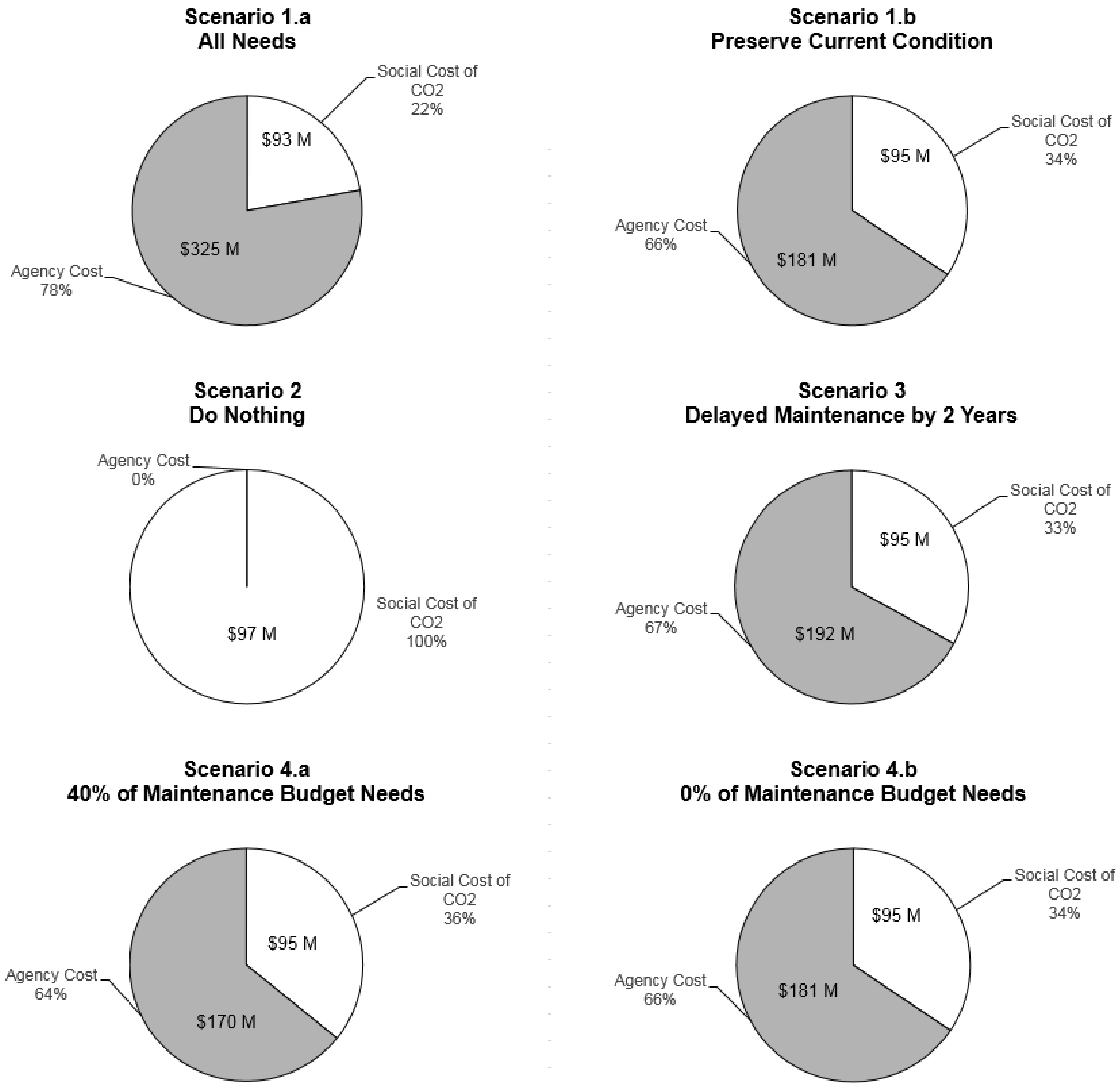


Figure C-28. Social costs of CO_2 over time.

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