APPENDIX G

Procedure to Quantify Consequences of Delayed Maintenance of Lighting

The purpose of roadway lighting is to provide better nighttime visibility conditions for drivers to improve safety and reduce the risk of nighttime crashes (Lutkevich et al. 2012). "Lighting enables the driver to recognize the geometry and condition of the roadway at extended distances" (ILDOT 2013). Street lighting improves visibility and safety of pedestrians on sidewalks, reduces crime, as well as well-lit crosswalks improve visibility of pedestrians for incoming vehicles. Lighting also increases road aesthetics and helps to maintain operating speed during nighttime (Markow 2007). Delaying maintenance on the lighting system will not only impact agency future maintenance and replacement costs but will also affect safety increasing the likelihood of car crashes at nighttime. Figure G-1 shows the procedure to quantify the consequences of delayed maintenance of lighting systems.

Figure G-1. Procedure to quantify the consequences of delayed maintenance of lighting.

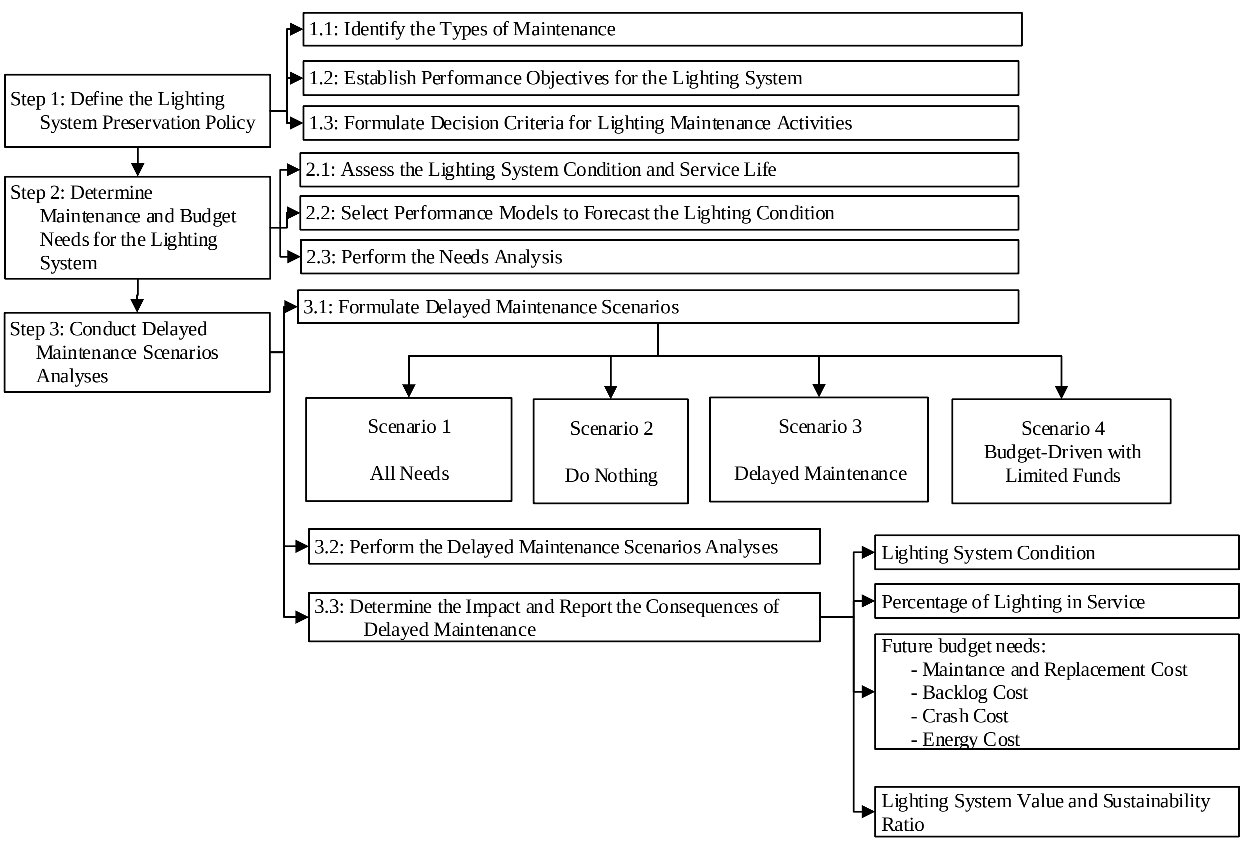


***Figure G-1. Procedure to quantify the consequences of delayed maintenance of lighting*.**

G.1 Step 1: Define the Lighting System Preservation Policy

The initial step in the procedure is to define a preservation policy for the lighting system. To some extent the level at which the policy is defined depends on the data that an organization has available on its lighting assets. For instance, if an organization has detailed data on the inventory, with details on structural supports and their condition, electrical systems, and dates of the most recent relamping of each system, then it is possible to define a relatively comprehensive and specific policy. However, many organizations maintain a basic database of lighting assets with very high-level inventory and little or no condition data. In these cases, the preservation policy is necessarily more straightforward, identifying under what circumstances relamping is performed. The following sections describe the sub-steps in defining a system preservation policy regardless of the level of detail of the inventory and condition data that an organization maintains. The example presented in this Appendix illustrates a case for an agency that has only summary inventory data on its database as available in most of the DOTs.

G.1.1 Identify the Types of Maintenance

In this step the agency must determine what types of maintenance should be considered in the preservation program. This is complex by the fact that the term "maintenance" is often defined differently between agencies. Common maintenance terms for lighting used by DOTs are defined as follows:

Preventive maintenance is usually targeted on switch gear, control cabinets, (Markow 2007) or cleaning. The frequency of luminaire cleaning is calculated based on the Luminaire Dirt Depreciation (LDD) factor which accounts for characteristics such as "luminaire type, mounting height, environment of the luminaire location (urban or rural setting), traffic volume, and roadway offsets" (AASHTO 2005).

Immediate maintenance, also called remedial, is often performed in emergency safety hazard cases, such as knockdowns, cable breaks, and switch gear problems (Markow 2007).

Corrective maintenance is usually performed on fixture failures and any problems with the lamp or ballast (Markow 2007).

Worst-first maintenance is performed on "underground breaks from deteriorated systems resulting in failures from salt water and freeze-thaw in winter" (Markow 2007).

Group replacement / Routine maintenance: Lighting systems can be replaced at a specified interval. In the European Union, where lighting is of high quality with very few outages, the lighting systems are relamped typically every three or five years (Wilken et al. 2001). Older facilities may need to be updated to the current light sources, energy conservation standards and wiring (ILDOT 2013 and MnDOT 2010). There is an incentive to replace high-pressure sodium (HPS) luminaires with light-emidding diodes (LEDs) which are more energy efficient and last longer.

Some DOTs perform mostly corrective maintenance due to low manpower and non-existing processes for selecting which lighting asset components are maintained. Accidents and electrical faults get priority and monthly night runs are performed to find problems. Work orders are processed via various management systems, for example SAP, where history of maintenance costs are saved. Often there are not statewide policies and management plans for lighting, so the maintenance practices differ from region to region. However, it is recommended by FHWA to include a maintenance plan (cleaning and replacement) in the life-cycle cost analysis during design stages, as in some cases, more expensive durable and corrosion-resistant lighting can provide the best benefit to cost ratio (Lutkevich et al. 2012).

In the lighting model developed in this study, the number and type of maintenance activities for the preservation of the lighting system has been streamlined to include proactive relamping (replacing lamps prior to failure), reactive relamping (replacing lamps after they have failed), and installation of new LED lights to replace HPS lights.

G.1.2 Establish Performance Objectives for the Lighting System

In this step the agency should select the performance measures that will be used to setup target objectives as a benchmark to analyze the effects of delaying maintenance. When selecting lighting performance measures it is important to consider the different factor categories that contribute to lighting performance, such as lighting metrics, overall performance, and condition. Table G-1 shows lighting performance categories with contributing factors.

Lighting assets are usually inspected at least once a year to decide if they will be replaced or not based on their condition. These inspections can range from assessment by patrols to ultrasonic nondestructive testing (Markow 2007). Figure G-2 shows an example of a lighting assessment form developed by NJDOT, the evaluation looks into categories such as geometric factors of the road, lighting operational factors, environmental factors, and accident rate. Lighting operation is assessed on a five-step scale from A to E. In general, agencies focus on fixing failed lights as opposed to lamps that are below a condition threshold.

Table G-1. Lighting performance categories and important contributing factors.

Category	Important Data or Factor
Lighting metrics	illuminance, “amount of light that falls onto a surface” (Lutkevich et al. 2012) [lumens/ft^2]
Overall performance	asset functionality (Markow 2007)
	customer complaints (Markow 2007)
Condition	asset age (Markow 2007)
	structural condition of support system (Markow 2007)
	corrosion on support system (Markow 2007)

Source: Markow 2007 and Lutkevich et al. 2012

EVALUATION FORM FOR CONTROLLED ACCESS FACILITY (CONTINUOUS FREEWAY LIGHTING)									LIGHTING FORM 1
	RATING								
CLASSIFICATION FACTOR	1	2	3	4	5	UNLIT WEIGHT (A)	LIGHTED WEIGHT (B)	DIFF (A-B)	RATING X(A-B)
GEOMETRIC FACTORS									
NUMBER OF LANES	4		6		≥8	1.0	0.8	0.2	
LANE WIDTH	>12′	12′	11′	10′	≤9′	3.0	2.5	0.5	
MEDIAN WIDTH	>40′	24′-39′	12′-23′	4′-11′	0-3′	1.0	0.5	0.5	
SHOULDERS	10′	8′	6′	4′	0	1.0	0.5	0.5	
SLOPES	≥8:1	6:1	4:1	3:1	2:1	1.0	0.5	0.5	
CURVES	0-½°	½-1°	1-2°	2-3°	3-4°	13.0	5.0	8.0	
GRADES	<3%	3.0-3.9%	4.0-4.9%	5.0-6.9%	>7%	3.2	2.8	0.4	
INTERCHANGE FREQUENCY	21,000′	16,000′	10,500′	5000′	<5,000′	4.0	1.0	3.0	
						GEOMETRIC TOTAL			
OPERATIONAL FACTORS									
LEVEL OF SERVICE (ANY DARK HOUR)	A	B	C	D	E	6.0	1.0	5.0	
						OPERATIONAL TOTAL			
ENVIRONMENTAL									
% DEVELOPMENT	0%	25%	50%	75%	100%	3.5	0.5	3.0	
OFFSET TO DEVELOPMENT	200′	150′	100′	50′	<50′	3.5	0.5	3.0	
						ENVIRONMENTAL TOTAL			
ACCIDENTS									
RATIO OF NIGHT-TO-DAY ACCIDENTS	1.0	1.0-1.2	1.2-1.5	1.5-2.0	2.0*	10.0	2.0	8.0	
						ACCIDENT TOTAL			
* CONTINUOUS LIGHTING WARRANTED	**GEOMETRIC TOTAL** **OPERATIONAL TOTAL** **ENVIRONMENTAL TOTAL** **ACCIDENT TOTAL** **SUM** **WARRANTING C ONDITION**				=______. =______. =______. =______. =______ **POINTS** = **95 POINTS**				

Source: NJDOT 2014
Figure G-2. Example of a lighting assessment form.

Lighting standards, warrants, and design criteria are found in the Roadway Lighting Design Guide (AASHTO 2005), and the ANSI / IES RP-8-14: American National Standard Practice for Roadway Lighting. For example, the ANS/IES standard defines the recommended luminance based on roadway classification (major, collector, local) and pedestrian traffic at night (significant, lesser, low traffic) (MnDOT 2010). The lighting equipment consists of luminaires, support system, and service cabinets. Luminaires have optical, electrical, and mechanical components Lighting support system consists of mast arm, pole, and foundation.

The targets clearly depend largely upon what performance measures are established. The following are examples of targets an agency might set for common performance measures:

- Percentage of lighting in certain condition
- Lighting age
- Degree of lighting material degradation

Other lighting performance measures used by DOTs are shown in Table G-2.

Table G-2. Examples of other performance measures for lighting.

Performance Measure	Description	Source
Function as intended	90% of the total luminaries of the combined sign and highway lighting are functioning as intended	FDOT 2015
Crash rate	Ratio of night-to-day accidents	NJDOT 2014
Energy savings	Percentage of LEDs, Percentage converted to LEDs	

In this study, the lighting model predicts the percentage of lights in operation at a given point. When lights fail, this reduces energy costs but increases accident costs. The model predicts that the nighttime crash rate increases 33 percent at a given location when lighting is not functioning (equivalent to a 25 percent decrease for adding lighting to an unlit location). This crash rate estimate is based on a recent synthesis on effects of lighting on safety (Wilken et al. 2001). To use the model, targets are specified for proactive relamping, reactive replacement of failed lamps, and conversion to LED. The model predicts the needs for reactive replacement of failed lamps, and funds necessary to achieve the target values during the analysis period.

G.1.3 Formulate Decision Criteria for Maintenance Activities

The decision criteria should specify what activities are needed based on the lighting condition and the cost of those activities. Later in the process, it is necessary to further determine the impact of the activities on lighting condition. If an agency has implemented a lighting management system, then this information may already be specified; otherwise it is necessary to define the maintenance activities. In order to simplify the decision criteria, maintenance activities are divided into two major groups:

Proactive maintenance: Agencies not only fix failed lamps, but also lamps that have a greater probability of failure if they are below a certain threshold. For example, a DOT can plan for rewiring of old direct bury wires to reduce future failures and proactively retrofit lighting fixtures to LED.

Reactive maintenance: Agencies fix lamps only when they have failed. For example, Colorado Department of Transportation Region 5, assess condition of a certain percentage of their lighting asset inventory and replace any lights that are not in good condition. Other agencies, such as Texas Department of Transportation, monitor condition remotely via voltage, where a drop in voltage indicate a knockdown or a burnt out lamp.

In this study, the lighting model simulates reactive maintenance by allowing the user to specify what percent of failed lamps are replaced each year (ideally 100 percent but possibly less in practice if maintenance is delayed). Further, the model simulates proactive replacements by allowing the user to specify the probability threshold at which lamps are proactively replaced. For example, if the user enters a value of 90 percent, then any lamps that have a 90 percent chance of failure (or greater) in a given year are replaced. Also, the user can specify what percentage of conventional HPS fixtures are converted to LED each year.

G.2 Step 2: Determine Maintenance and Budget Needs for the Lighting System

G.2.1 Assess the Lighting System Condition

Lighting service life is usually determined based on agency experience, professional judgment and manufacturer's data. However, assets are often "repaired or replaced as soon as they fail without regard to service life" (Markow 2007). Group relamping based on lamp mortality curve based on manufacturer's data is a common maintenance method (CDOT 2006). DOTs perform nighttime drive-by inspections looking for problems such as flickering or knockdowns, usually in less than three month intervals (Markow 2007). Highway lighting is monitored more often, e.g. every two weeks.

The median life expectancy for lighting ranges between 25 to 30 years for structural components, 1 to 4 years for lamps, 7 years for ballast, 18 years for control panels and 16 years for luminaires, as Table G-3 shows. LED lamps are not shown on the table. These are projected to last 10 to 20 years (similar to that shown for a typical luminaire), but when they fail the LED fixture must be replaced rather than an individual lamp.

Table G-3. Lighting life expectancy.

Components and Material	No. of Responses	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
Structural Components						
Tubular Steel	12	10	40	25.4	25	25
Tubular Aluminum	9	10	40	26.1	25	30
Cast Metal	2	15	30	22.5	22.5	−
Wood Posts	2	25	40	32.5	32.5	−
High mast or tower	11	10	50	28.6	30	30
Lamps						
Incandescent	3	1	5	2	1	1
Mercury Vapor	6	3	5	4	4	4
High pressure	15	1	6	3.6	4	5
Sodium						
Low-pressure	3	1	5	3	4	4
Sodium						
Metal halide	9	1	5	2.9	3	2
Fluorescent	1	−	−	5	−	−
Other components						
Ballast	9	2	25	9.7	7.5	10
Photocells	11	1	10	5.2	5	5
Control panels	7	10	25	18.2	20	20
Luminaires	2	5	25	16.25	16.25	−

Notes: −, value is undefined for the particular distribution. When distribution is based on only one data point, its value is

shown in the Mean column.
Source: NCHRP Synthesis 371 – Markow 2007

G.2.2 Select Performance Models to Forecast the Lighting System Service Life

Lighting performance can be estimated based on condition or age. A condition-based approach requires periodical condition assessment inspections to develop deterioration models. An age-based approach estimates the remaining life from historical records of construction and reconstruction. For lighting systems an age-based approach is frequently the only viable approach as it is often not practical to establish a condition assessment program for lighting, and it is difficult to visually inspect conditions of key components, such as lamps. Popular performance models used to forecast lighting service life include:

- Exponential functional form (Szary et al. 2005)
- Weibull distribution (Ford et al. 2012)

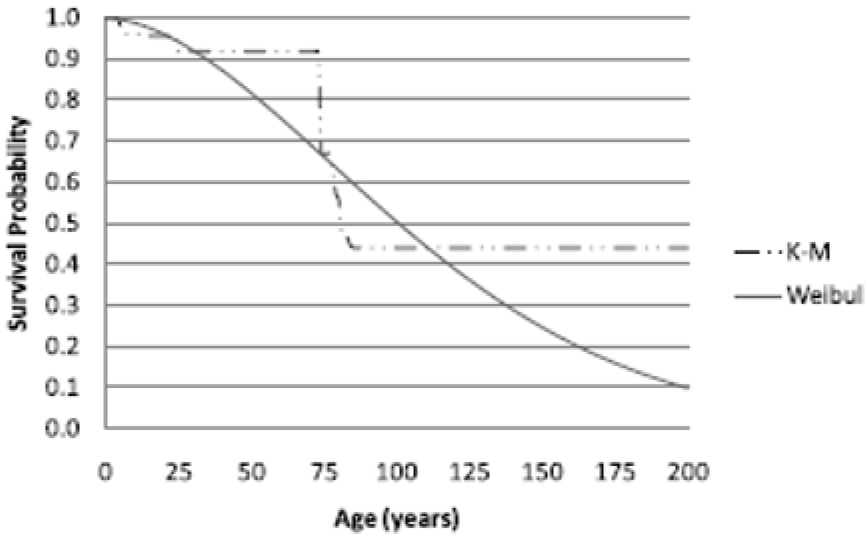
Table G-4 shows an example of a Weibull regression model to predict roadway lighting life.

Table G-4. Weibull regression model of roadway lighting life (end-of-life = historical replacement interval).

Life Expectancy Factor	Parameter Estimate, β	t-Statistic
Constant	-4.674	-1.479
Normal Annual Temperature (°F)	0.172	2.933
Material type indicator (1 if metal pole, 0 otherwise)	-1.023	-7.964
Mounting location indicator (1 if on sign, 0 otherwise)	1.069	3.113
Functional class indicator (1 if on interstate, 0 otherwise)	0.437	3.440
Fixture height indicator (1 if less than 30 feet, 0 otherwise)	-0.350	-1.391
Baseline Ancillary Factors	**Parameter Estimate, β**	**t-Statistics**
Shape Factor, β	1.764	14.201
Scaling Factor, α	123.609	10.372
Model Statistics		
Number of observations	229	
Log-likelihood Function at Convergence	-177.88	
Restricted Log-likelihood Function	-328.68	

Source: Ford et al. 2012

The lighting failure probability can follow a Weibull distribution as Figure G-3 shows. Failure probability increases for metal and tall poles. Whereas factors such as “warmer climate, sign mounting and interstate” location tend to extend the life (Ford et al. 2012). A Kaplan-Meier (K-M) estimate distribution is also shown in Figure G-3. The prediction of Weibull model was validated against the non-parametric K-M estimate (Ford et al. 2012).



Source: Ford et al. 2012

Figure G-3. Lighting failure probability curve.

In this study, the lighting model uses a Weibull distribution that predicts lamp failure. Default values for the model were populated based on findings from the NCHRP Report 713 and expert knowledge. This modeling approach is consistent with existing practices, but focuses on failure of the shortest-lived element of a lighting unit, the lamp, and does not account for the need for maintenance of structural or electrical components. Figure G-4 illustrates the cumulative failure probability assumed in the model for HPS lamps and LED fixtures. As indicated in the figures, HPS lamps are predicted to last 2-3 years, and LED fixtures are predicted to last approximately 20 years based on this model.

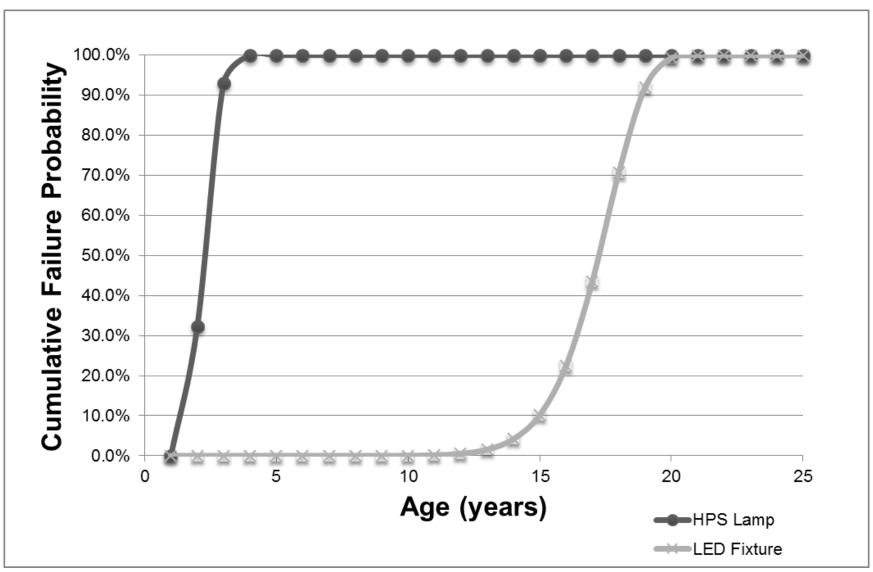


Figure G-4. Modeled failure rate of HPS lamps and LED fixtures.

G.2.3 Perform the Needs Analysis

The needs analysis is performed as follows using the lighting model developed for the research:

1. HPS lamps and LED fixtures are grouped by age in years, and calculations are made for each 1-year age bin (e.g., 2-year old HPS lamps).
2. Three types of needs are considered: (1) needs for replacing failed HPS lamps and LED fixtures; (2) needs for proactively replacing HPS lamps or LED fixtures with a specified probability of failure, and (3) needs for conversion from HPS to LED lamps.
3. The model predicts the number of failed lamps and fixtures for each 1-year age bin using the distributions shown in Figure G-4. The percentage of failed lamps/fixtures replaced is specified as input, as is the average amount of time between the initial failure and lamp/fixture replacements.
4. For each age bin the model predicts the likelihood of failure in the next year for the HPS lamps and LED fixtures that do not fail in the current year. If the failure likelihood exceeds a specified percentage, then these lamps/fixtures are replaced.
5. The model predicts the number of HPS lights converted to LED. The percentage converted is an input specified by analysis year and the same value is applied regardless of age.
6. Agency costs are tabulated for reactive replacements, proactive replacements, and conversion to LED.
7. Energy costs are tabulated, accounting for the savings in energy cost from not operating failed lights, and the reduced energy costs of LED relative to HPS.
8. Crash costs due to failed lights are tabulated, accounting for the number of failed lights and failure duration. The model predicts increased crash costs from nighttime crashed based on the model assumptions detailed further below.
9. Lamp/fixture ages are increased by one year, and the analysis is repeated for the next year until the end of the analysis period.

Table G-5 lists the default lighting model assumptions with the corresponding notes of the source. Regarding replacement costs, the cost for HPS is based on data from Virginia described in the literature (VTRC 2015). This study estimates annual maintenance costs, including costs of relamping and other maintenance, and expresses them as a unit cost per watt per year. These are captured in the average replacement cost of $480 for HPS based on the assumption that HPS fixtures are typically 250W and are relamped every two years. This reference estimates similar costs for LED on a per year basis. However, the unit cost per replacement is significantly higher, $3,000 per replacement, since LED fixtures are replaced less frequently. If replacement work is performed reactively rather than proactively (unscheduled rather than scheduled), it is assumed to add 10 percent to the cost. Other parameters, including energy costs, time to replace failed lamps/fixtures, crash-related parameters, and the existing inventory are based on data collected in the case study.

Table G-5. Default lighting model assumptions.

Parameter		Value	Notes
Annual energy cost per fixture ($)	HPS	78.40	Energy cost of 7 cents per kWh assumed based on case study assuming 4,000 hours of energy use per fixture, with 250W per fixture for HPS, 150W for LED
	LED	47.04	
Replacement cost per unit ($)	HPS, scheduled	480	(VTRC 2015): determined based on analysis of annual maintenance costs for HPS lighting: 10% increase assumed for unscheduled replacement
	HPS, unscheduled	528	
	LED, scheduled	3,000	Case study data: 10% increase assumed for unscheduled replacement
	LED, unscheduled	3,300	
Time to replace failed lamp/fixture (days)		14	Case study data
Annual VMT for portion on network with lighting (millions)		1,484.64	Case study data: 12% of network of interstates, other freeway/expressway and other principal arterials.
Nighttime crash rate for portion of network with lighting (crashes per million VMT)		1.65	Case study data: note the analysis assumes half of all crashes occur at night
Average crash cost ($/crash)		100,000	Case study data
Initial number of fixtures	HPS	4,510	
	LED	5,723	

G.3 Step 3: Conduct Delayed Maintenance Scenarios Analyses

G.3.1 Formulate the Delayed Maintenance Scenarios

Table G-6 defines the set of scenarios evaluated for lighting maintenance. In Scenario 1, three different types of agency-desired maintenance policies are tested. Scenario 1.a approximates the current practices of an agency in located in western state. In this case, lighting maintenance is performed in a reactive manner: when an HPS lamp or LED fixture fails, it is replaced, and the agency is gradually transitioning from use of HPS to LED. However, the agency does not perform proactive replacements of HPS or LED. Scenario 1.b describes a scenario in which failed HPS lamps and LED are replaced, and the agency is also proactively gradually transitioning from use of HPS to LED over a 10 year period. In addition, the agency proactively replaces units with high probability of failure, reducing replacement costs and the time that lights are out. Scenario 1.c is similar to Scenario 1.a, except that in this case no additional fixtures are transitioned from HPS to LED.

In Scenario 2, replacement of failed lamps is delayed by 10 years. In Scenario 3, the replacement of failed lamps/fixtures is delayed by 5 years. In Scenario 4 different constraints are placed on maintenance work. In Scenario 4 only a percentage of failed lamps are replaced due to limited budget. Percentages are include 90 percent in Scenario 4.a, 75 percent in Scenario 4.b, and 50 percent in Scenario 4.c.

Table G-6. Key elements to analyze delayed maintenance scenarios for lighting.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 10 years	Results
Lighting System Database Inventory	Weibull models for predicting likelihood of lamp or electrical failure Another alternative to model deterioration is a straight-line service life, based on original design life	1. All Needs a. Failed lamps/fixtures are replaced in 2 weeks. HPS is replaced with LED over a 10-year period. No additional proactive replacements are performed. b. Failed lamps/fixtures are replaced in 2 weeks. HPS is replaced with LED over a 10-year period. Additionally, lamps/fixtures are proactively replaced when their failure probability exceeds 90%. c. Failed lamps/fixtures are replaced in 2 weeks. No proactive replacements are performed and no additional fixtures are converted to LED. 2. Do Nothing All lamp/fixture replacements are deferred for 10 years. 3. Delayed Maintenance All lamp/fixture replacements are deferred for 5 years. After the deferral period failed lamps are replaced in two weeks. No proactive replacements are performed and no additional fixtures are converted to LED. 4. Budget-Driven with Limited Funds a. Only 90 percent of failed lamps/fixtures are replaced due to limited budget b. Only 75 percent of failed lamps/fixtures are replaced due to limited budget c. Only 50% of failed lamps/fixtures are replaced due to limited budget Replacements that are performed in 2 weeks. No proactive replacements are performed, and no additional fixtures are converted to LED.	Analytical Tool Spreadsheet based model that incorporates probability of failure Reports • Impact on condition due to delayed maintenance • Agency costs of scheduled and unscheduled maintenance • Agency costs of converting HPS to LED where applicable • Agency energy costs • Increased user accident costs from loss of lighting

G.3.2 Perform the Delayed Maintenance Scenarios Analyses

Table G-7 shows the results of the scenarios described in Table G-6. Agency costs of replacing lamps/fixtures reactively (unscheduled) and proactively (scheduled); the cost of converting from HPS to LED; excess crash costs; energy costs; and total costs are reported. A discount rate of 7 percent is used for the discounted costs. The minimum percentage of fixtures in service over the period of analysis and at the end of the 10 years are also reported.

Table G-7. Summary of scenario analysis results for lighting.

Scenario		Description	Agency Replacement Costs[1]			Excess Crash Cost[1]	Energy Cost[1]	Total Cost[1]	Discounted Total Cost	% in Service	
			Reactive	Proactive	LED					Min	End
1		All Needs									
	a.	HPS Replaced with LED.	$3.64 M	0	13.53	$1.95 M	$5.50 M	$24.64 M	$19.13 M	100	100
	b.	Proactive Replacement	$1.80 M	2.47	13.53	$0.88 M	$5.50 M	$24.20 M	$18.73 M	100	100
	c.	100% of Failures Replaced	$8.95 M	0	0	$5.03 M	$6.22 M	$20.21 M	$14.78 M	100	100
2		Do Nothing	0	0	0	$305.66 M	$3.05 M	$308.71 M	$215.06 M	55	55
3		Delayed Maintenance (5 years)	$5.34 M	0	0	$144.24 M	$4.82 M	$154.41 M	$123.44 M	56	100
4		Budget-Driven with Limited Funds									
	4.a	90% of Failures Replaced	$8.56 M	0	0	$17.53 M	$6.09 M	$32.19 M	$23.37 M	98	98
	4.b	75% of Failures Replaced	$7.87 M	0	0	$39.65 M	$5.85 M	$53.38 M	$38.49 M	95	95
	4.c	50% of Failures Replaced	$6.35 M	0	0	$89.07 M	$5.31 M	$100.74 M	$72.02 M	87	88

[1] At the end of year 10

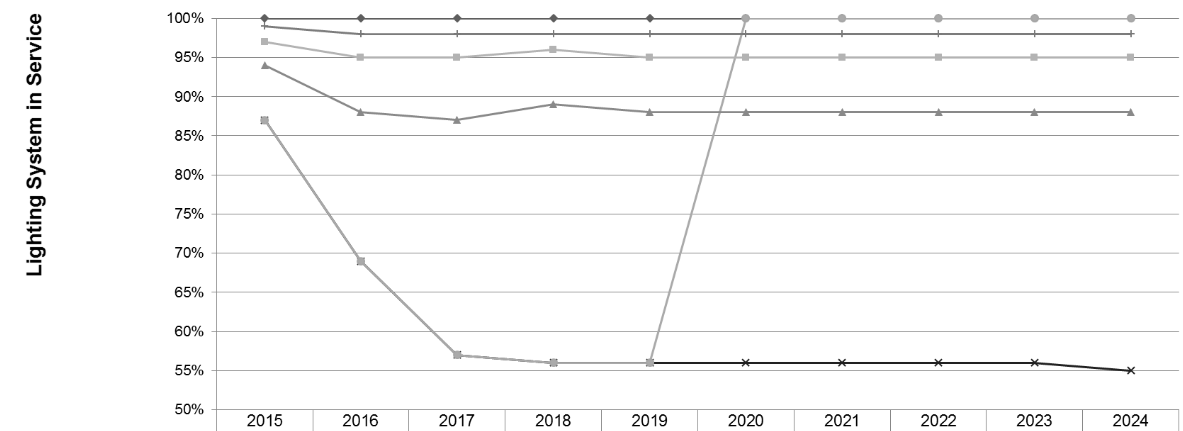
G.3.3 Determine the Impact of Delayed Maintenance and Report the Consequences

To quantify the consequences of delayed maintenance, the results of delayed maintenance scenarios are compared to the baseline scenario from the needs analysis. Six scenarios out of eight the scenarios defined in Table G-7 are selected to show the consequences of delayed maintenance.

Consequences on the Lighting System in Service

Prior to the scenario analyses 100 percent of the lighting system is in service and 56 percent of the lights are LED.

Figures G-5 and G-6 display the percentage of the lighting system in service throughout the analysis period. For Scenario 1.a, where 100 percent of failures are replaced, the entire lighting system is in service during the analysis period. This is representative of Scenario 1.b and 1.c, as well. For Scenario 2, where lamp replacements are delayed by 10 years, the percentage of lighting system in service drops to 55 percent in year 10. For Scenario 3, where lamp replacements are delayed by 5 years, the percentage of lighting system in service drops to 56 percent in year 5 and then recovers to 100 percent in year 6. For Scenario 4.a, where 90 percent of failures are replaced, 98 percent of the lighting system is in service during the analysis period. For Scenario 4.b, where 75 percent of failures are replaced, 95 percent of the lighting system is in service during the analysis period. For Scenario 4.c, where 50 percent of failures are replaced, 88 percent of the lighting system is in service during the analysis period.



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Scenario 1 - 100 % of Failures Replaced	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Scenario 2 - Do Nothing	87%	69%	57%	56%	56%	56%	56%	56%	56%	55%
Scenario 3 - Delay by 5 Years	87%	69%	57%	56%	56%	100%	100%	100%	100%	100%
Scenario 4.a - 90% of Failures Replaced	99%	98%	98%	98%	98%	98%	98%	98%	98%	98%
Scenario 4.b - 75% of Failures Replaced	97%	95%	95%	96%	95%	95%	95%	95%	95%	95%
Scenario 4.c - 50% of Failures Replaced	94%	88%	87%	89%	88%	88%	88%	88%	88%	88%

Figure G-5. Percentage of lighting system in service.

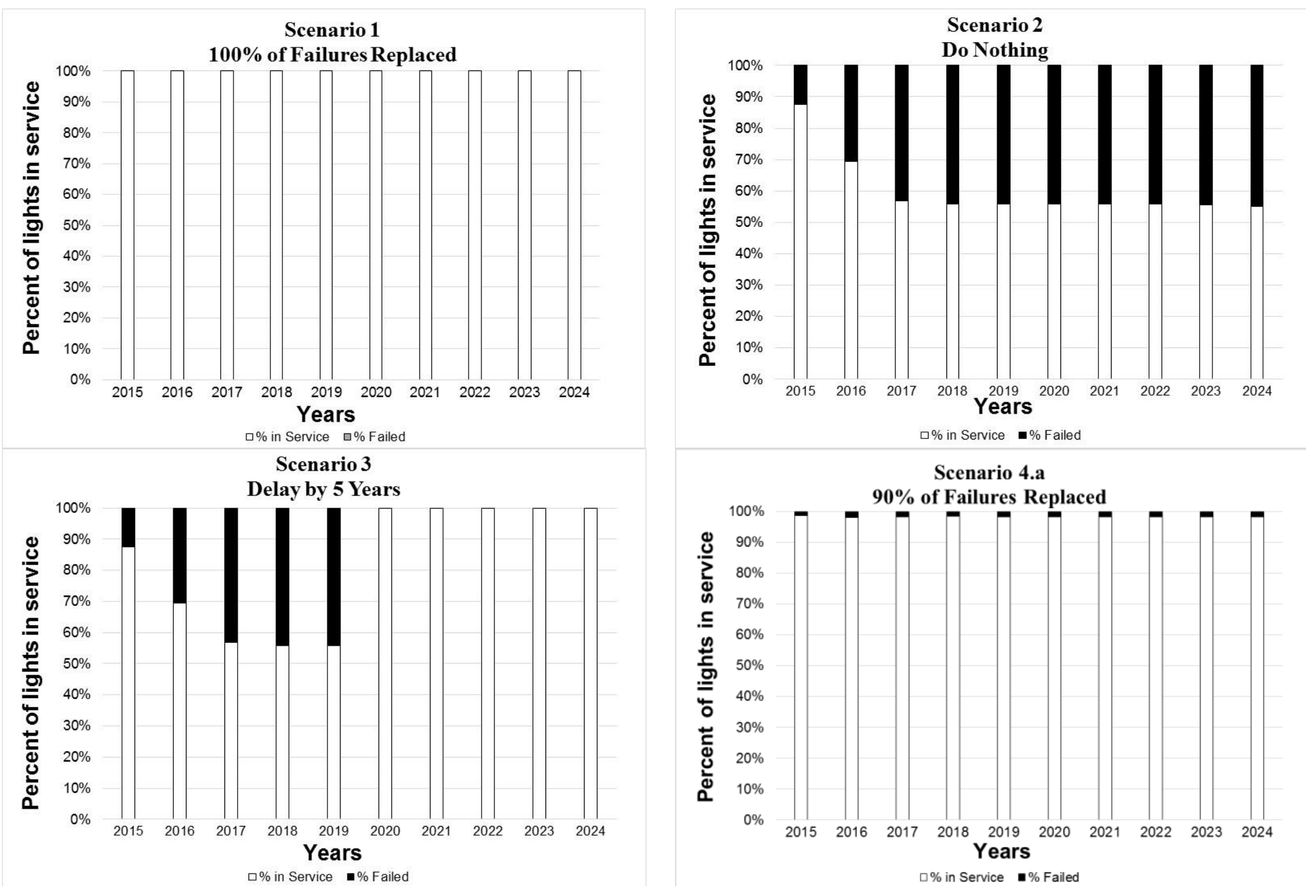


Figure G-6. Lighting system condition category over time.

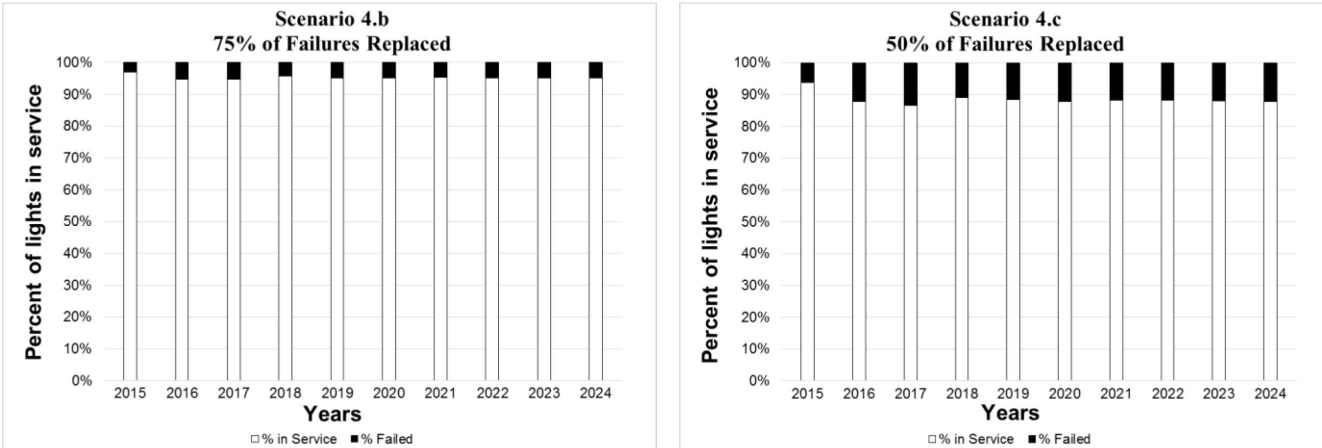


Figure G-6. Lighting system condition category over time. (Continued)

Consequences on Future Budget Needs

Figure G-7 shows the predicted costs by year for Scenario 1.a, which best represents current agency practice. The figure shows proactive and reactive replacement costs by year, costs for conversion from HPS to LED, energy costs, crash costs, and total costs. Figure G-8 shows predicted costs by year for Scenario 1.c, in which failed lamps and fixtures are replaced, but no additional fixtures are converted to LED. Relative to Scenario 1.a there are no conversion costs, but these are substituted with higher energy costs and higher costs for reactive replacements. Note that over the 10-year analysis period considered by the model Scenario 1.c is slightly cheaper than Scenario 1.a. However, the benefits of LED over HPS are expected to manifest themselves over a longer period than the 10-year analysis period, and in any case the purpose of the present analysis is to demonstrate the effects of delaying maintenance, not the life-cycle implications of converting from HPS to LED. Figure G-9 shows the predicted costs for Scenario 3, in which all work is deferred for 5 years. In this scenario increased crash costs become the dominant cost over the deferral period, rising to approximately $20 million per year (equivalent to an additional 2-3 fatalities per year). Figure G-10 shows the predicted percentage of lighting units in service for this scenario, illustrating the drop in HPS lighting in service over the deferral period.

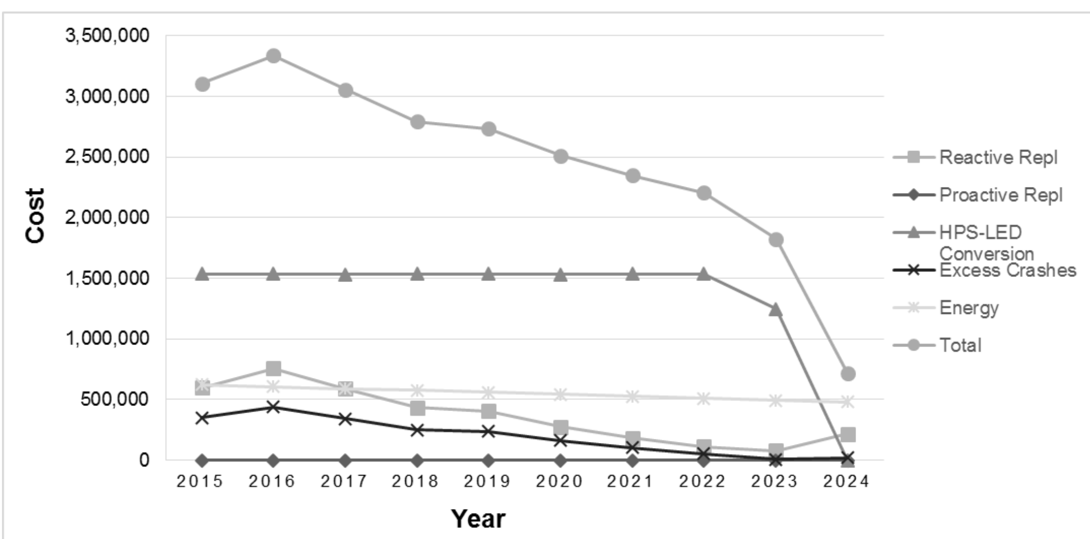


Figure G-7. Costs by year, Scenario 1.a.

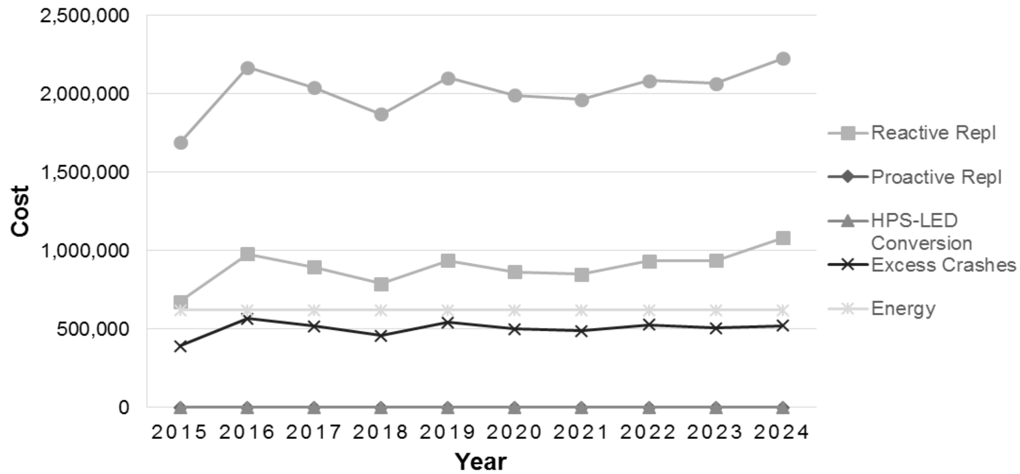


Figure G-8. Costs by year, Scenario 1.c.

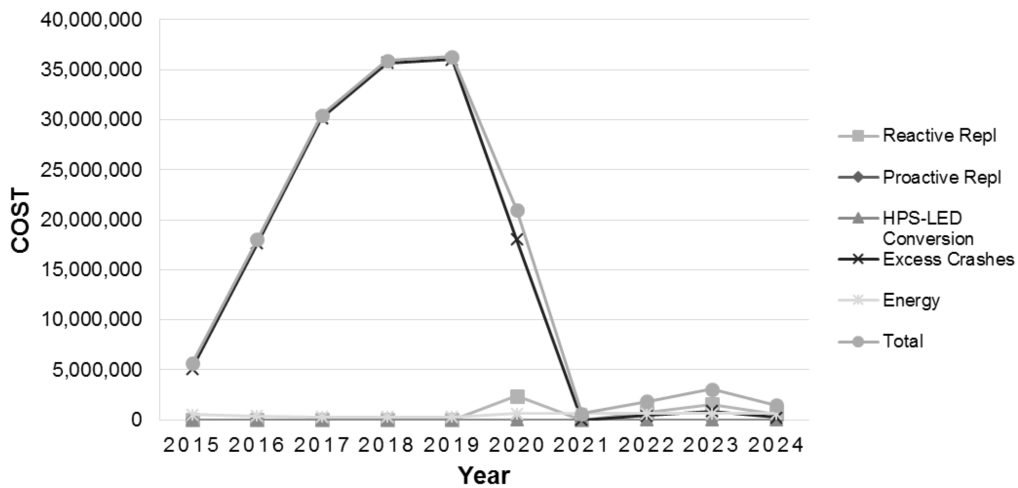


Figure G-9. Costs by year, Scenario 3.

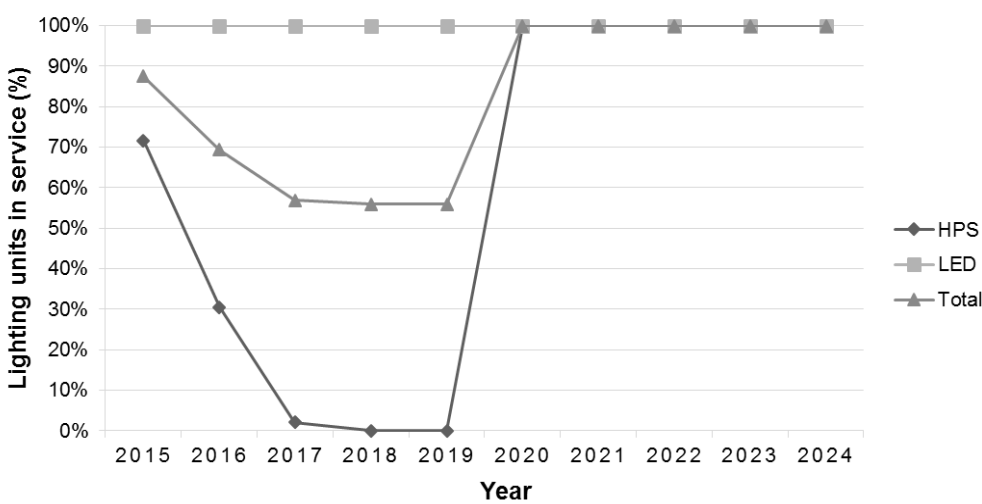


Figure G-10. Lighting units in service by year, Scenario 3.

Figure G-11 shows the unfunded backlog for each scenario throughout the analysis period. For Scenario 1, where 100 percent of failures are replaced, there is no backlog. For Scenario 2, where lamp replacements are delayed by 10 years, the backlog is $2.7 million at year 10. For Scenario 3, where lamp replacements are delayed by 5 years, the backlog reaches $2.4 million in year 5 but starting year 6 there is no backlog costs. For Scenario 4.a, where 90 percent of failures are replaced, the backlog does not reach over $112,000 during the 10-year analysis period. For Scenario 4.b, where 75 percent of failures are replaced, the backlog reaches $316,000 at the end of the analysis period. For Scenario 4.c, where 50 percent of failures are replaced, the backlog reaches $768,000 at the end of the analysis period.

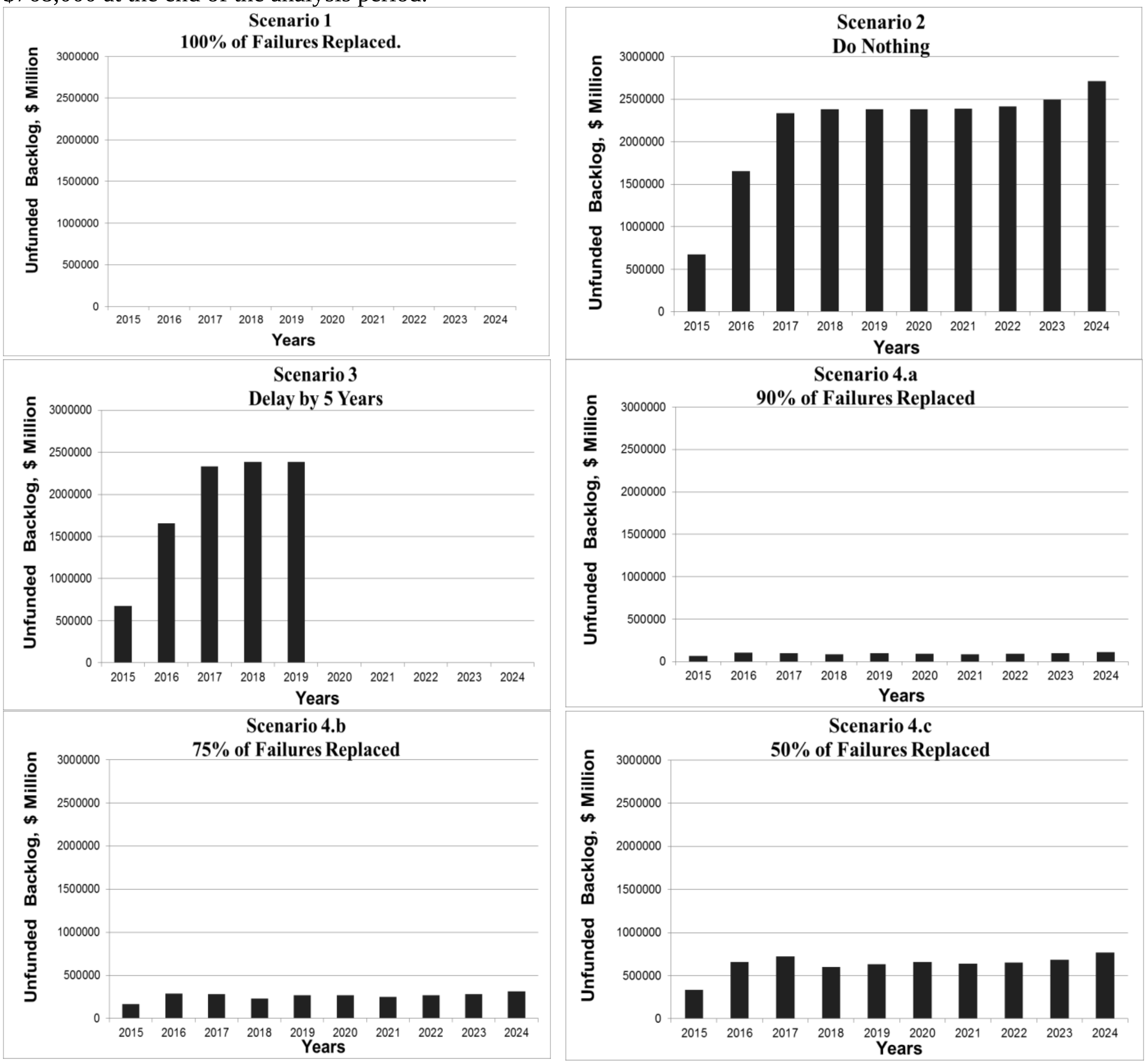
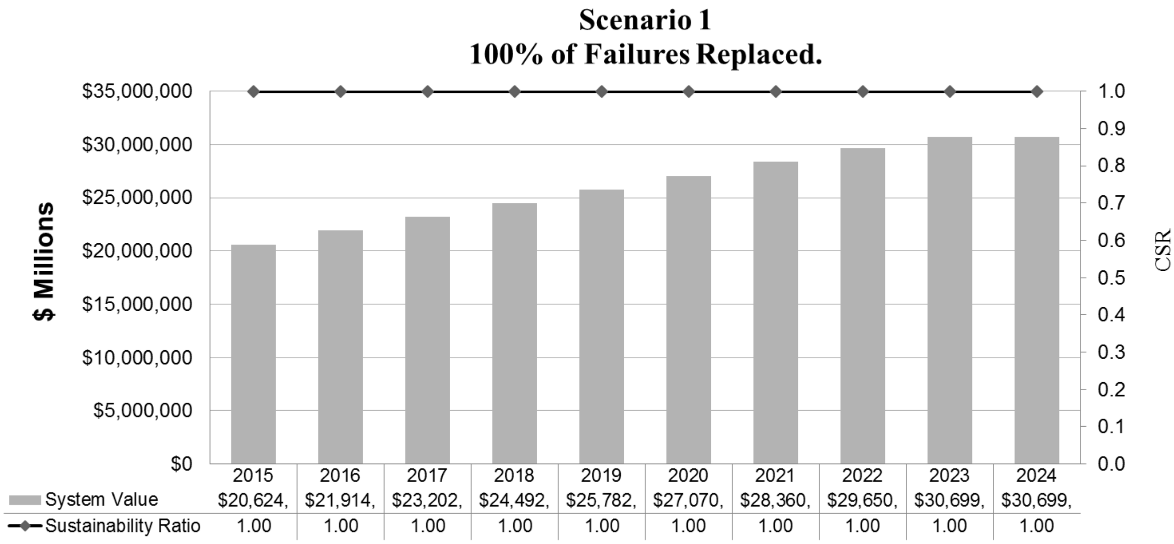


Figure G-11. Unfunded backlog for each scenario over the analysis period.

Figure G-12 shows changes of the lighting system value together with the lighting sustainability ratio (LSR) over the analysis period of 10 years. LSR indicates on a scale 0 to 1 the percentage of asset needs that are funded each year.

For Scenario 1, where 100 percent of failures are replaced, the network value increases from the initial $20.6 million to $30.7 million at the end of the analysis. For Scenario 2, where lamp replacements are delayed by 10 years, the system value gradually decreases during the analysis period down to $16.9 million in the last year. For Scenario 3, where lamp replacements are delayed by 5 years, the asset value decreases in the first five years to $17.2 million and then increases to $19.3 million for years 6 through 10. Scenario 4.a, where 90 percent of failures are replaced, maintains the asset value at $19.2 million. Scenario 4.b, where 75 percent of failures are replaced, maintains the asset value at approximately $19.1 million. Scenario 4.c, where 50 percent of failures are replaced, maintains the asset value at approximately $18.6 million.



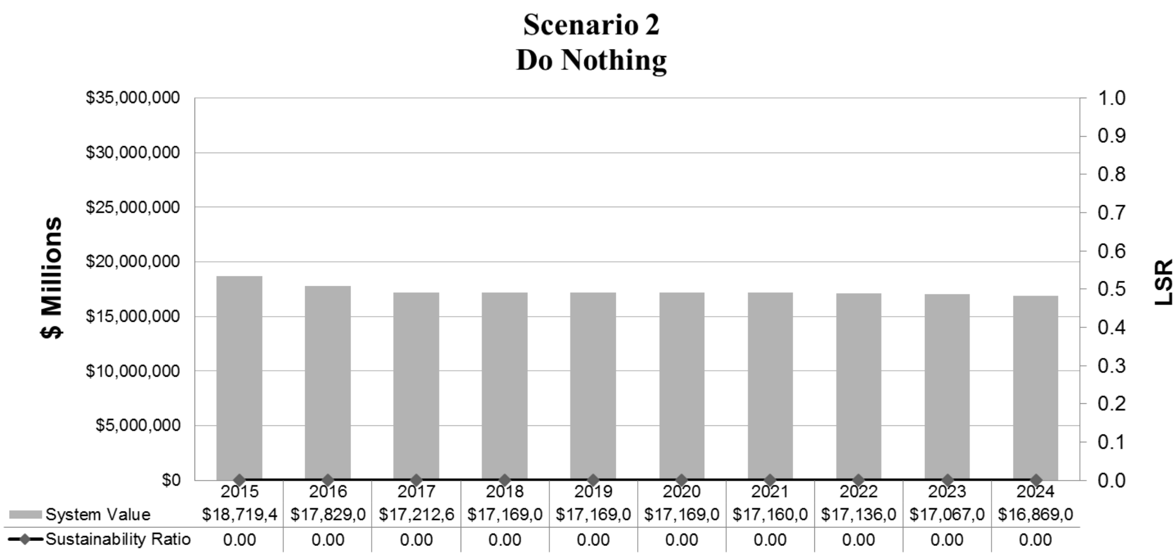
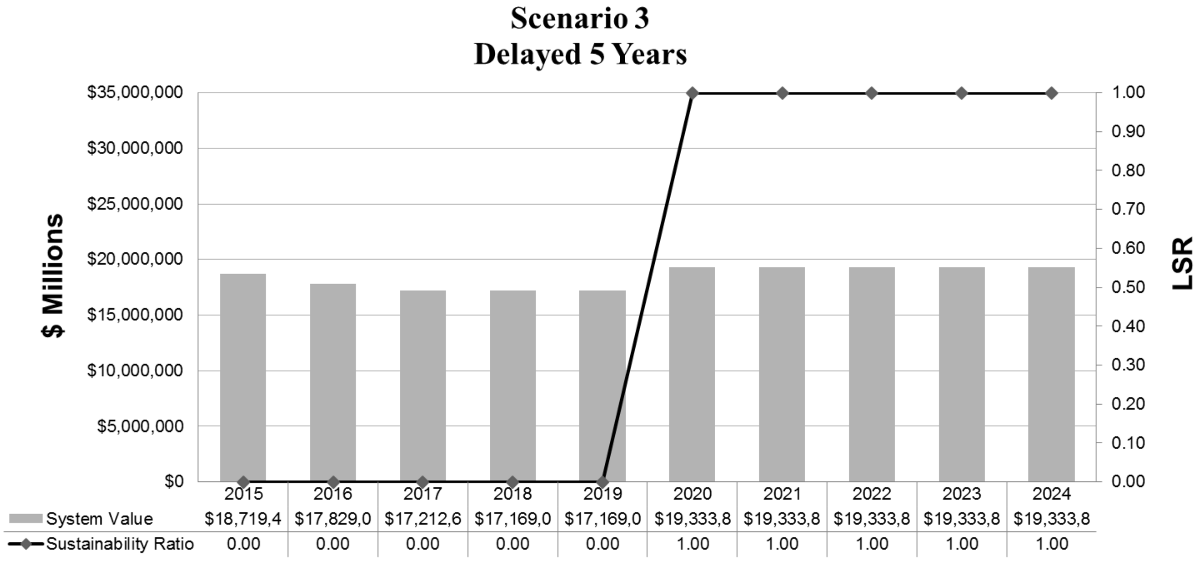
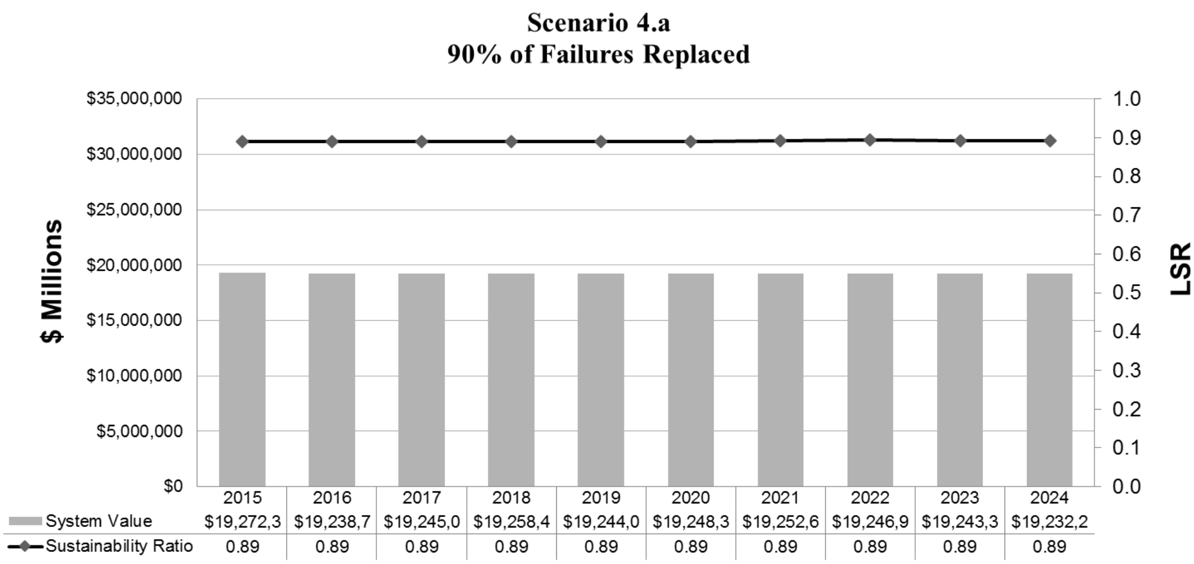


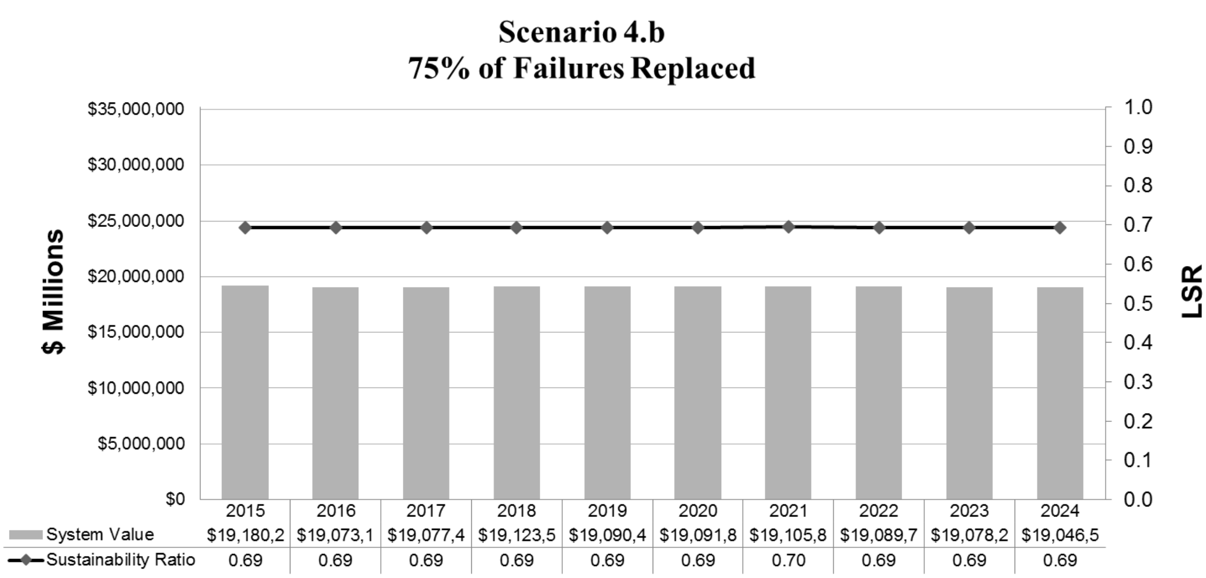
Figure G-12. Lighting system value and sustainability ratio over the analysis period.



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
System Value	$18,719,4	$17,829,0	$17,212,6	$17,169,0	$17,169,0	$19,333,8	$19,333,8	$19,333,8	$19,333,8	$19,333,8
Sustainability Ratio	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
System Value	$19,272,3	$19,238,7	$19,245,0	$19,258,4	$19,244,0	$19,248,3	$19,252,6	$19,246,9	$19,243,3	$19,232,2
Sustainability Ratio	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
System Value	$19,180,2	$19,073,1	$19,077,4	$19,123,5	$19,090,4	$19,091,8	$19,105,8	$19,089,7	$19,078,2	$19,046,5
Sustainability Ratio	0.69	0.69	0.69	0.69	0.69	0.69	0.70	0.69	0.69	0.69

Figure G-12. Lighting system value and sustainability ratio over the analysis period. (Continued)

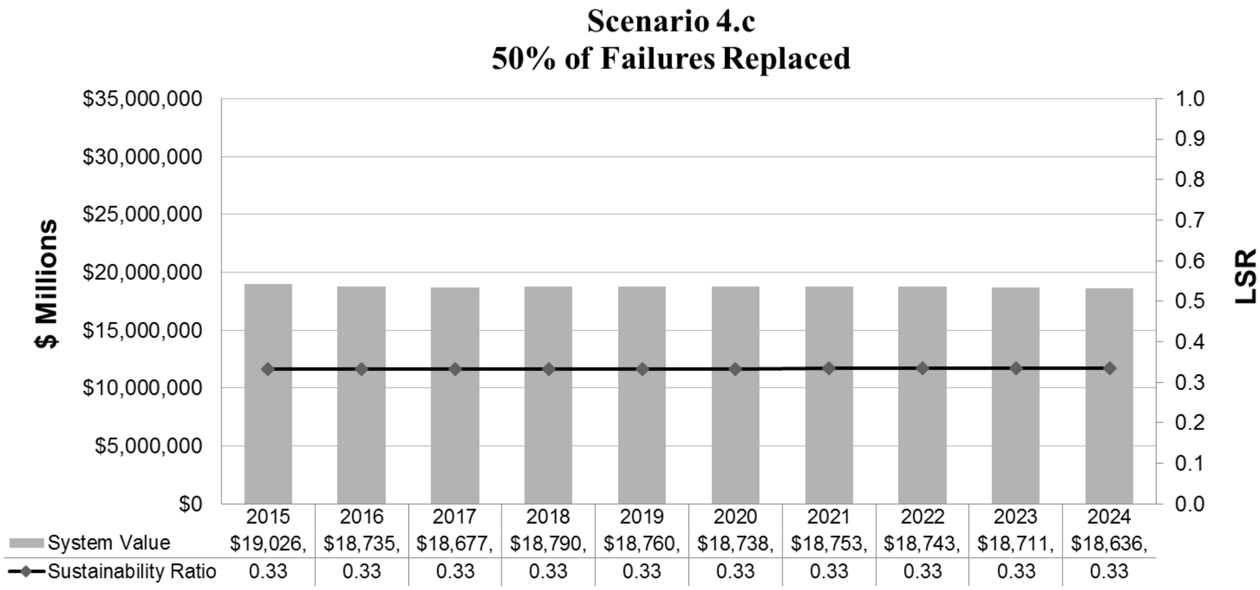


Figure G-12. Lighting system value and sustainability ratio over the analysis period. (Continued)

G.4 Summary

The scenario results that were summarized in Table G-7 in the previous section clearly demonstrate the effects of delaying maintenance to the lighting system, affecting the condition and the agency costs. Delaying maintenance results in increased numbers of lighting fixtures out of service. This reduces energy costs, but these savings are more than offset by increased crash costs. Specific results for the case study include the following:

- Proactive replacement of lamps/fixtures that are likely to fail increases the agency costs slightly, but reduces overall costs as result of the savings in crash costs. This is illustrated by comparing Scenario 1.b to Scenario 1.a, in which proactive replacements are performed, results in an increase in agency costs of approximately $0.7 million over 10 years relative to Scenario 1.a, but a reduction in overall costs of $0.4 million.

- Conversion from HPS to LED increases costs over a 10-year period, as illustrated by comparing Scenario 1.a, and Scenario 1.c. However, over a longer period conversion, it would be more beneficial given the increased life of LED fixtures compared to HPS. This analysis was intended to demonstrate effects of delaying maintenance rather investing in LED conversion.

- Delaying maintenance always results in increased costs in the scenarios evaluated, whether the delay takes the form of increasing time to respond to failures. Reducing the percentage of failed lamps/fixtures that are replaced (Scenario 4), or imposing a deferral period (Scenario 3). The impacts are most clearly demonstrated by comparing Scenario 3, Scenario 4 and Scenario 1.c. In Scenario 1.c, failures are replaced, but no proactive work is performed, and no HPS fixtures are converted to LED. In Scenario 3, no maintenance work is performed for 5 years, then the same policy is performed as for Scenario 1.c.

- The 5-year deferral period simulated in Scenario 3 reduces the allocated budget or agency costs of the work performed by approximately $5.5 million, and saves approximately $1.4 million in energy costs. However, deferring maintenance increases the overall life cycle costs by approximately $108.6 million due to increased crash costs. Also, the lighting system value by the fifth year of deferral decreases by $13.5 million, as almost half of the lighting system is not in service.

- The 10-year deferral period simulated in Scenario 2 reduces the agency costs by approximately $8.9 million, and approximately $3.2 million in energy costs. However, deferring maintenance increases overall life cycle costs by approximately $200.3 million due to increased crash costs. Also, the lighting system value by the tenth year of deferral decreases by $13.8 million, as almost half of the lighting system is not in service.

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