APPENDIX I

Procedure to Quantify Consequences of Delayed Maintenance of Highway Signs

The purpose of highway signs is to "communicate the rules, warnings, guidance, and other highway agency information that drivers, bicyclists, and pedestrians need to safely and efficiently navigate roads and streets" (McGee 2010). Signs can be categorized based on their function as regulatory, warning, and guide signs. Their good condition is crucial for traffic safety. Signs that are not properly maintained have reduced retroreflectivity, visibility and do not perform properly and compromise the safety of road users. Figure I-1 shows the procedure to quantify the consequences of delayed maintenance of highway signs.

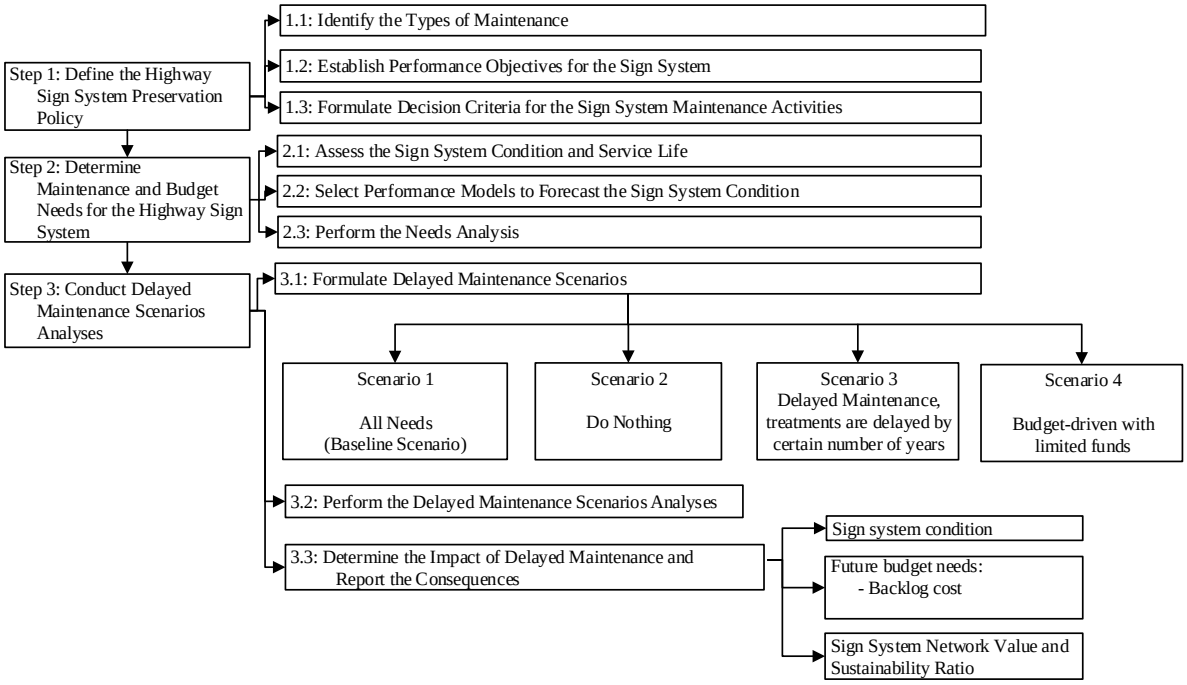


Figure I-1. Procedure to quantify the consequences of delayed maintenance of signs.

I.1 Step 1: Define the Highway Sign System Preservation Policy

The preservation policy for the highway sign system is usually formulated by a central office that provides policies for maintenance, specifications for materials, and criteria to allocate funding. Sign retroreflectivity must correspond to the Manual on Uniform Traffic Control Devices (MUTCD) standards. In addition, condition of sheeting and support, and percent of signs lasting as per manufacturer specifications are monitored over time. (Markow 2007).

I.1.1 Identify the Types of Maintenance Activities

Majority of DOTs use a combination of national standards and their own guidelines for sign maintenance practices. ASTM standards differentiate between Type I, II, III, IV, VIII, IX, or XI depending on the sheeting surface. Sign backing is usually made from aluminum; however, it can be also made from wood or plastic. Frequent types of post-mounted signs include wood post, U-channel steel post, square or round tube steel post, and I-beam steel post (McGee 2010). Sign standards, warrants and design criteria are described in the MUTCD (FHWA 2009) and ASTM D4956. Table I-1 shows the sign sheeting types and applications defined by the ASTM standards.

Table I-1. ASTM sign sheeting types.

Type	Description	Typical Construction	Suggested Use	Typical Applications
I	Medium Intensity	Enclosed lens	None provided	Permanent highway signing. Construction zone device, and delineators.
II	Medium high-intensity	Enclosed lens	None provided	Permanent highway signing. Construction zone device, and delineators.
III	High-Intensity	Encapsulated glass beads	None provided	Permanent highway signing. Construction zone device, and delineators.
IV	High-Intensity	Microprismatic	None provided	Permanent highway signing Construction zone device, and delineators
V	High-Intensity	Metallized microprismatic	None provided	Delineators
VI	Elastomeric high-intensity	Vinyl microprismatic	None provided	Orange temporary roll-up warning signs traffic cone collars, and post bands
VII	Super-high-Intensity	Microprismatic	Medium and long road distances	Permanent highway signing Construction zone device, and delineators
VIII	Super-high-Intensity	Microprismatic	Medium and long road distances	Permanent highway signing Construction zone device, and delineators

Table I-1. ASTM sign sheeting types. (Continued)

Type	Description	Typical Construction	Suggested Use	Typical Applications
IX	Very-high-Intensity	Microprismatic	Short road distances	Permanent highway signing. Construction zone device, and delineators.
X	Super-high-Intensity	Microprismatic	Medium road distances	Permanent highway signing. Construction zone device, and delineators.

Source: Carlson and Lupes 2007

A sign inventory database includes additional information to support the development of preservation programs including (ODOT 2015):

- Location: roadway ID, highway direction, milepost, GPS coordinates, side of road, distance from the edge of pavement.
- Sign properties: sign number, recycle count, sign width and height, substrate, sheeting, install date, facing direction, nighttime retroreflectivity and inspection date.
- Sign support: number of posts, their type, size, and installation date.

Table I-2 shows an example of sign inventory and condition elements.

Table I-2. Example of sign inventory and condition elements.

Data Element	Description
Sign Identification Number	Unique number identifying sign
Location	Route name, distance, etc. depending on location reference system; could also be GPS latitude/longitude
Sign Code	Usually MUTCD designation
Sign Position	Location of sign to road (left, right, Overhead)
Offset	Distance from edge of pavement
Height	Height of sign above road level
Sign Size	Width and height of sign
Sheeting Type	Grade of retroreflective material
Installation Date	Date when sign installed
Post/Support Type	Type of sign support (e.g., wood, tube)
Inspection Items	**Description**
Sign Condition	Quality of sign based on visual inspection
Retroreflectivity	Measured valued or visual assessment condition
Maintenance Activity	Type of maintenance last performed
Inspection/Maintenance Date	Date when sign was last inspected or maintained
Inspector	Name or initials of person who inspected or maintained sign
Comments	Supplementary notes about the sign

Source: McGee 2010

FHWA (2009) provides the following guidance on maintenance of signs:

- "Maintenance activities should consider proper position, cleanliness, legibility, and daytime and nighttime visibility (see Section 2A.09). Damaged or deteriorated signs, gates, or object markers should be replaced.
- To assure adequate maintenance, a schedule for inspecting (both day and night), cleaning, and replacing signs, gates, and object markers should be established. Employees of highway, law enforcement, and other public agencies whose duties require that they travel on the roadways should be encouraged to report any damaged, deteriorated, or obscured signs, gates, or object markers at the first opportunity.
- Steps should be taken to see that weeds, trees, shrubbery, and construction, maintenance, and utility materials and equipment do not obscure the face of any sign or object marker.
- A regular schedule of replacement of lighting elements for illuminated signs should be maintained." (FHWA 2009).

The types of maintenance for highway signs can be classified as preventive and corrective activities (Markow 2007). The Maintenance of Signs and Sign Supports: A Guide for Local Highway and Street Maintenance Personnel (FHWA-SA-09-025) provides specific examples of sign maintenance activities as follows (McGee 2010):

Preventive maintenance involves sign cleaning, vegetation control, anti-theft measures and sign support adjustments (McGee 2010).

Corrective (immediate) maintenance activities applied to signs that need to be repaired or replaced immediately. It is due to events such as vandalism, vehicle collision, damaged by natural forces, or once it reaches its service life. Poor condition or absence of regulatory signs "could result in or contribute to a severe crash", therefore they need to be "replaced or repaired within hours of the agency having notice of them missing, down, or damaged" (McGee 2010).

For example, Missouri DOT typically considers sign maintenance as corrective in nature. Work is identified either through nighttime inspection sign logs, drive by visual inspection, or customer calls. Work includes replacement of signs, plumbing the post, replacing the post, or trimming vegetation that blocks the visibility of the sign. There is no replacement cycle and signs are replaced as needed since there are a variety of ages amongst signs in a given area. The nighttime sign logs conducted every two years is the primary method for identifying signs that require maintenance. Sign replacement can be also decided on retroreflectivity measures from field inspection, or scheduled based on their expected service life (FHWA 2009).

I.1.2 Establish Performance Objectives for the Highway Sign System

In this step the agency should select the set of performance measures that will be used to show the effects of delaying maintenance. In selecting sign performance measures, it is important to consider the different causes of failure, such as (Markow 2007):

- decrease in retroreflectivity
- color fading
- daytime/nighttime legibility
- structural condition
- corrosion
- dirt accumulation
- vandalism (e.g., graffiti, bullet holes)
- age

Highway sign performance categories and important contributing factors are shown in Table I-3.

Table I-3. Highway sign performance categories and contributing factors.

Category	Important Data or Factor	Source
Overall Performance	Percent of the system functioning as intended	NCHRP 632 (Cambridge Systematics et al. 2009)
Condition	Retroreflectivity	(Markow 2007)
	Color fading / legibility	(Markow 2007)
	Structural condition	(Markow 2007)

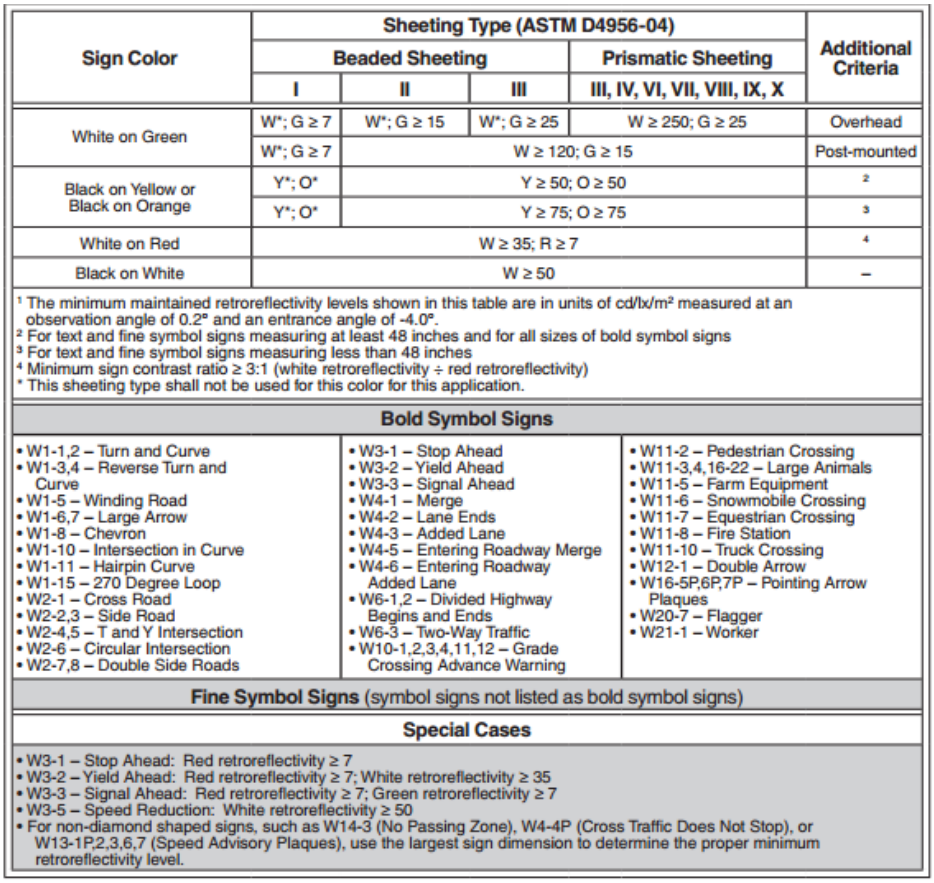
Individual performance measures can also be tied to condition states using a simplified scale as the five-tier scale developed by Florida DOT for overhead sign structures as shown in Table I-4.

Table I-4. Example of condition states for signs used by Florida DOT.

487 – Overlane sign structure horizontal member	488 – Overlane sign structure vertical member
1. There is no evidence of active corrosion and the coating system is sound and functioning as intended to protect the metal surface.	1. There is no evidence of active corrosion and the coating system is sound and functioning as intended to protect the metal surface.
2. There is little or no active corrosion. Surface corrosion had formed or is forming. The coating system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.	2. There is little or no active corrosion. Surface corrosion had formed or is forming. The coating system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.
3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.	3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.
4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of the element.	4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of the element.
5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or service ability of the unit.	5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or service ability of the unit.

Source: NCHRP 713, Thompson et al. 2012

Several DOTs focus only whether a sign is deficient or not. Deficiency can be defined by retroreflectivity. MUTCD requires minimum retroreflectivity levels depending on the sheeting type and symbol sign type, as Figure I-2 shows. CDOT uses three condition indicators for signs; percent of signs faded, percent of signs that are not straight or have damaged posts or breakaway devices not working, and percent of signs not readable at night. The rating for the first two indicators (i.e., signs faded, and damaged posts or nonworking breakaway devices) ranges from 4 (0 percent of damaged signs) to 0 (greater than 15 percent of damaged signs). There is also a condition indicator rating for retroreflectivity readings (mcd/lx/m^2), which ranges from 4, greater than 200 mcd/lx/m^2, to 0, 49 mcd/lx/m^2 or less. Annual inspections are also performed on 700 random locations statewide in 3 out of 10 sample set. These ratings are used to compute a letter grade from A to F for the Maintenance Level of Service (MLOS).



Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Post-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			2
	Y*; O*	Y ≥ 75; O ≥ 75			3
White on Red	W ≥ 35; R ≥ 7				4
Black on White	W ≥ 50				–

[1] The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m² measured at an observation angle of 0.2° and an entrance angle of -4.0°.
[2] For text and fine symbol signs measuring at least 48 inches and for all sizes of bold symbol signs
[3] For text and fine symbol signs measuring less than 48 inches
[4] Minimum sign contrast ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type shall not be used for this color for this application.

Bold Symbol Signs

- W1-1,2 – Turn and Curve
- W1-3,4 – Reverse Turn and Curve
- W1-5 – Winding Road
- W1-6,7 – Large Arrow
- W1-8 – Chevron
- W1-10 – Intersection in Curve
- W1-11 – Hairpin Curve
- W1-15 – 270 Degree Loop
- W2-1 – Cross Road
- W2-2,3 – Side Road
- W2-4,5 – T and Y Intersection
- W2-6 – Circular Intersection
- W2-7,8 – Double Side Roads
- W3-1 – Stop Ahead
- W3-2 – Yield Ahead
- W3-3 – Signal Ahead
- W4-1 – Merge
- W4-2 – Lane Ends
- W4-3 – Added Lane
- W4-5 – Entering Roadway Merge
- W4-6 – Entering Roadway Added Lane
- W6-1,2 – Divided Highway Begins and Ends
- W6-3 – Two-Way Traffic
- W10-1,2,3,4,11,12 – Grade Crossing Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3,4,16-22 – Large Animals
- W11-5 – Farm Equipment
- W11-6 – Snowmobile Crossing
- W11-7 – Equestrian Crossing
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow
- W16-5P,6P,7P – Pointing Arrow Plaques
- W20-7 – Flagger
- W21-1 – Worker

Fine Symbol Signs (symbol signs not listed as bold symbol signs)

Special Cases

- W3-1 – Stop Ahead: Red retroreflectivity ≥ 7
- W3-2 – Yield Ahead: Red retroreflectivity ≥ 7; White retroreflectivity ≥ 35
- W3-3 – Signal Ahead: Red retroreflectivity ≥ 7; Green retroreflectivity ≥ 7
- W3-5 – Speed Reduction: White retroreflectivity ≥ 50
- For non-diamond shaped signs, such as W14-3 (No Passing Zone), W4-4P (Cross Traffic Does Not Stop), or W13-1P,2,3,6,7 (Speed Advisory Plaques), use the largest sign dimension to determine the proper minimum retroreflectivity level.

Source: FHWA 2009

Figure I-2. Minimum maintained retroreflectivity levels.

In this study, the sign model defines condition categories (A, B, C, D, F) based on the percentage of deficient signs in a sector. Sign deficiency means that there is a problem with a sign face or post which can be fixed either by maintenance or replacement. Table I-5 shows the sign condition categories defined in the model used in this study.

Table I-5. Sign condition categories based on percentage of deficient signs.

Condition category	Percent of deficient signs in a group	
	Lower limit	Upper limit
A	0.00	5.00
B	5.01	10.00
C	10.01	14.99
D	15.00	19.99
F	20.00	100.00

I.1.3 Formulate Decision Criteria for Highway Sign Maintenance Activities

This step involves determining the decision criteria to trigger signs maintenance activities. Based on the Asset Management Data Collection Guide (AASHTO-AGC-ARTBA 2006) as a reference, the following maintenance activities are considered: preventive maintenance only due to good condition (signs comply with MUTCD standards and local standards), needs repair (missing bolts, leaning, damaged posts, in need of cleaning), and needs replacement (damaged or illegible).

Field inspections are used to determine the signs conditions to be compared to the requirements established by the agency. For example, Florida's MRP handbook has specific desired maintenance conditions for signs. During inspections, each sign is evaluated per the MRP standard to determine if maintenance is needed. Signs do not meet the MRP standards in the following cases.

1. Sign installations including panels and posts leaning more than 1 inch per foot.
2. There is missing connecting hardware, nuts, and bolts.
3. Sign panels are attached to columns below a fuse cut.
4. Bottom of sign panel is installed more than 2 inches above or below the fuse cut.
5. Aluminum "C" clamps are used to attach a sign panel to a post.
6. Cantilever signs are not installed according to the design standards.
7. Brackets are installed improperly.
8. A cantilever sign wider than 4 feet does not meet current design standard 11861.
9. Sign rotation causes the sign message to become unreadable. (Note: In urban areas, "NO PARKING" signs may be rotated 30° to 40° toward traffic).
10. Signs fail to convey the intended message due to lack of reflectivity, fading or surface accumulations. (Note: All signs shall be reflectorized or illuminated to show the same shape and color in day and night conditions).
11. Height and offset of mile markers are not installed according to the Design Standards. (Note: For MRP purposes, a height tolerance of up to 3 inches and an offset tolerance of up to 12 inches are permitted).
12. Aluminum posts greater than 3-1/2 inches in diameter are not installed on a slip base or breakaway support and are not shielded by barrier wall or guardrail.
13. A slip base or breakaway support is covered with soil.
14. A slip base or breakaway support more than 4 inches above the finished ground as measured at the center.
15. A single post installation is prohibited by the Design Standards.
16. Single post installations of a sign or sign cluster wider than 60 inches unless specifically allowed by the Design Standard Index 11860, or District Design Office.
17. A sign on a slip base is installed without a concrete footing.
18. The edge of a sign panel is installed less than 2 feet from the face of guardrail.
19. The height and lateral offset of a sign panel is not installed according to the Design Standards.
20. Damage to a sign column that compromises its function.
21. U-channel steel posts heavier than 3 pounds per foot have no breakaway support.
22. Steel post support stubs protrude more than 4 inches above the ground.

The main objective of the preservation activities is to maintain the retroreflectivity of signs above the minimum threshold using the methods shown in Table I-6 (Carlson and Lupes 2007).

Table I-6. Methods for maintaining minimum retroreflectivity of signs.

Method	Description	Advantages	Disadvantages
Combination of methods or other method	Agency blends different methods or adopts customized method (based on engineering study)	Customized method to achieve effectiveness and efficiency	Potentially labor and time intensive depending on level of engineering study.
Night time visual inspection	Assessment conducted by a trained inspector following procedures	Overall condition is evaluated	Subjective and overtime pay for late-evening labor.
Measured sign retroreflectivity	Signs are measured with an instrument following procedures	Direct measurement. No subjectivity factor in the evaluation	Time consuming and unable to evaluate other factors effecting sign's appearance.
Expected sign life	Signs replaced based on age, warranty, or degradation of sign sheeting	Adapted to local conditions that influence the expected service life	Sign sheeting type and expected life needs to be known as well as the installation date of the sign.
Blanket replacement	Replacement of all signs at specified time intervals based on the shortest life of material used	Proactive approach Replaces all signs at once to minimize the probability of failure.	Potential waste of relatively new signs.
Control signs	Replacement of signs based on a sample set of control signs	Less labor intensive	Control sign sample set must be representative and monitored over time.

Source: Carlson and Lupes 2007

Most DOTs primarily rely on nighttime inspections and follow the expected sign life, control sign, or blanket replacement method to determine maintenance activities (Re and Carlson 2012). For example, Utah DOT identifies the percent of assets which are deficient within a station (section of highway). Based on this percentage, the station is given a letter grade for the level of maintenance required (i.e., A, B, C, D, and F).

In this study, the decision criteria for maintenance activities are based on a letter grade system. Signs in category A, with less than 5 percent deficiency, do not receive any action. Sign groups in category B, 100 percent of deficient signs, require maintenance to return to a non-deficient state. For sign groups in category C, 60 percent of deficient signs require maintenance, and 40 percent replacement to return to a non-deficient state. For sign groups in category D, 20 percent of deficient signs require maintenance and 80 percent replacement to return to a non-deficient state. Lastly, sign groups in category F require the replacement of all deficient signs.

I.2 Step 2: Determine Maintenance and Budget Needs for the Highway Sign System

I.2.1 Assess the Sign System Condition and Service Life

The MUTCD provides general guidelines on the condition assessment for signs, however it does not mention the surveys frequency (Re and Carlson 2012).

The MUTCD mentions the following condition assessment methods and maintenance activities (FHWA 2009):

- **"Visual Nighttime Inspection**—The retroreflectivity of an existing sign is assessed by a trained sign inspector conducting a visual inspection from a moving vehicle during nighttime conditions. Signs that are visually identified by the inspector to have retroreflectivity below the minimum levels should be replaced" (FHWA 2009).
- **"Measured Sign Retroreflectivity**—Sign retroreflectivity is measured using a retroreflectometer. Signs with retroreflectivity below the minimum levels should be replaced" (FHWA 2009).
- **"Expected Sign Life—**When signs are installed, the installation date is labeled or recorded so that the age of a sign is known. The age of the sign is compared to the expected sign life. The expected sign life is based on the experience of sign retroreflectivity degradation in a geographic area compared to the minimum levels. Signs older than the expected life should be replaced" (FHWA 2009).
- **"Blanket Replacement**—All signs in an area/corridor, or of a given type, should be replaced at specified intervals. This eliminates the need to assess retroreflectivity or track the life of individual signs. The replacement interval is based on the expected sign life, compared to the minimum levels, for the shortest life material used on the affected signs" (FHWA 2009).
- **"Control Signs**—Replacement of signs in the field is based on the performance of a sample of control signs. The control signs might be a small sample located in a maintenance yard or a sample of signs in the field. The control signs are monitored to determine the end of retroreflective life for the associated signs. All field signs represented by the control sample should be replaced before the retroreflectivity levels of the control sample reach the minimum levels" (FHWA 2009).
- **"Other Methods**—Other methods developed based on engineering studies can be used" (FHWA 2009).

These methods are classified into two main categories: assessment methods and management methods (Carlson and Lupes 2007). Assessment methods are nighttime visual inspections and retroreflectivity measurements. Management methods are expected sign life, blanket replacement, and control sign.

A survey conducted by Markow in 2007 found that most DOTs evaluates the sign condition periodically, while others repair or replace signs once they fail, or compare the current age with a predefined service life. Sign service life is determined based on the agency experience, professional judgment, and manufacturer's data. Life expectancy for sign sheeting ranges between 7 and 20 years, and for sign posts between 10 to 40 years (Markow 2007), as Table I-7 shows.

Most DOTs do not have sign life information in their databases. Therefore, it is a common management practice to identify the percentage of deficient signs in a sector without recording details of the individual signs condition.

Table I-7. Signs life expectancy.

Component and Material	No. of Responses	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
Sign Sheeting						
All Sheeting	17	7	20	11	10	15
Aluminum	3	7	40	19.8	11	-
Vinyl sheeting	2	5	7	6	6	6
Sign Posts						
Steel U-channel	10	10	40	18.0	15	10
Steel square tube	10	10	40	16	15	10
Steel round tube	3	15	40	23.3	15	15
Aluminum tube	1	-	-	10	-	-
Wood	3	15	20	16.7	15	15
Structural steel beam supports	2	25	30	27.5	27.5	-
Overhead sign bridges and support						
Steel sign bridge	12	10	50	30.8	30	30
Aluminum sign bridge	8	10	45	26.9	30	30
Overpass/bridge mounting	1	-	-	50	-	-

Notes: Values is undefined for the particular distribution. When distribution is based on data point. Its value is shown in the Mean column.
Source: NCHRP Synthesis 371 – Markow 2007

I.2.2 Select Performance Models to Forecast the Sign System Condition

Age, weather conditions, light exposure, and type of material all affect the deterioration of signs. To model the probability of failure, a Weibull distribution can be adopted to estimate the sign remaining life. Another alternative is to use a straight line deterioration model. In the literature, the following performance models are described for signs:

- Linear or quadratic mathematical equations are used to estimate sign retroreflectivity based on age, color, and sheeting type as Table I-8 shows. The development of these equations from condition data is described by Immaneni et al. (2009)

Table I-8. Examples of linear and quadratic performance models for predicting sign retroreflectivity.

Sign Color	Sign Type	Data Source	Equation $Y:R_a$ X: Sign age [year(s)]	R^2	Regression Standard Error	Linear Age Coefficient P-value	Quadratic Age Coefficient P-value	Regression Model P-value	Year at R_a = NCDOT minimum
White	I	FHWA	$Y=103.085 – 5.451x$	.52	19.1	<0.0001	-	<0.0001	15
	III	FHWA	$Y=304.089 – 4.815x$	.19	32.7	<0.0001	-	<0.0001	59
Yellow	I	FHWA	$Y=78.794 – 3.906x$	.39	17.0	<0.0001	-	<0.0001	15
	III	Purdue	$Y=-0.552x^2 + 5.644x + 193.01$	.26	33.6	0.0033	<0.0001	<0.0001	24
Red	I	NCSU	$Y=13.085 – 0.635x$	.37	3.0	<0.0001	-	<0.0001	14
	III	NCSU	$Y=59.632 – 2.658x$	.35	9.7	<0.0001	-	<0.0001	21
Green	I	FHWA	$Y=15.990 – 0.637x$	.31	3.4	<0.0001	-	<0.0001	19
	III	FHWA	$Y=53.386 – 1.345x$	.48	7.7	<0.0001	-	<0.0001	37

Source: Immaneni et al. 2009

- Weibull survival probability model. NCHRP Report 713 (Thompson et al. 2012) describes the development of a Weibull survival probability model from traffic sign inspection data. Table I-9 shows the parameters used in this model.

Table I-9. Weibull survival probability parameters.

Road Segment	Year of Inspection	Age of Signs	Actual Fraction Passing	Predict Fraction Passing	Markov Fraction Passing	Square of Deviation act-pred	Square of Deviation act-mean	Log Likelihood
RS00001	1994	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00001	1996	2	1.00	0.966	0.869	0.0012	0.0976	1.496
RS00001	1998	4	0.99	0.880	0.755	0.0121	0.0914	0.682
RS00001	2000	6	0.95	0.761	0.657	0.0356	0.0688	-1.071
RS00001	2002	8	0.89	0.627	0.571	0.0692	0.0410	-3.577
RS00001	2004	10	0.62	0.492	0.496	0.0163	0.0046	0.369
RS00001	2006	12	0.43	0.369	0.431	0.0037	0.0664	1.309
RS00001	2008	14	0.31	0.265	0.375	0.0020	0.1426	1.431
RS00001	2010	16	0.19	0.182	0.326	0.0001	0.2476	1.579
RS00002	1998	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00002	2000	2	0.96	0.966	0.869	0.0000	0.0742	1.581
RS00002	2002	4	0.88	0.880	0.755	0.0000	0.0370	1.584
RS00002	2004	6	0.73	0.761	0.657	0.0010	0.0018	1.510
RS00002	2006	8	0.64	0.627	0.571	0.0002	0.0023	1.571
RS00002	2008	10	0.51	0.492	0.496	0.0003	0.0315	1.561
RS00002	2010	12	0.42	0.369	0.431	0.0026	0.0716	1.392
RS00003	1996	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00003	1998	2	0.97	0.966	0.869	0.0000	0.0797	1.582
RS00003	2000	4	0.91	0.880	0.755	0.0009	0.0495	1.517
RS00003	2002	6	0.71	0.761	0.657	0.0026	0.0005	1.387
RS00003	2004	8	0.58	0.627	0.571	0.0022	0.0116	1.419
RS00003	2006	10	0.41	0.492	0.496	0.0068	0.0771	1.077
RS00003	2008	12	0.34	0.369	0.431	0.0009	0.1208	1.520
RS00003	2010	14	0.21	0.265	0.375	0.0030	0.2281	1.360

Coeff	Value
Median Years	9.88
Shaping param	1.87
Std. deviation	0.0819
Sum Loglike	49.852
Scaling param	12.025
Markov scaling	14.259
Mean passing	0.6876
SSE	0.3083
SST	3.2848
R-squared	0.9061

Source: Thompson et al. 2012

Transition condition matrices can also be used to model the deterioration or improvement in the signs condition over time. A description on how to develop these matrices from condition data follows.

Deterioration and improvement matrices from condition data

The performance of the highway sign system is modeled in the example using transition matrices to simulate deterioration or improvement in the signs condition. Condition categories (A, B, C, D, and F) are based on the percentage of deficient signs in a sector as defined previously in Table I-5. The parameters for the transition matrices are obtained from statistical analysis of historical data. The step-by-step process to develop the transition matrices from condition data is described in this section.

a. Extract data from the sign inventory to analyze deterioration and improvement trends for all the sign groups in the inventory. A sign group includes certain number of signs that are located along a roadway segment. As a reference, in the "Work Zone Road User Costs, Concepts and Applications" report (McGee 2010), provides guidelines about data for sign inventory. For the model described in this App, the minimum data include: number of signs in a group, and defective signs in a group. This step is done for all the years in the inventory

b. For two consecutive years (n and n+1), the percentage of defective signs are compare for each sign group and split into two categories: deteriorated and improved groups. Sign groups with a higher defective percentage in year n were compared to year n + 1 for the condition deterioration transition matrix, and sign groups with a lower defective percentage in year n +1 were compared to year n data for the improvement condition

transition matrix. There are five condition categories (A through F), based on the percentage of signs that are defective within a group.

c. Transition matrices are defined by the number of groups that move from one condition to another and by the increase or decrease of the deficient signs within a group in that category in year n+1. There are 15 deterioration condition transitions and 15 improvement transitions that can be experienced by each of the sign groups in the model.

d. For the deterioration transition matrix, the number of sign groups that deteriorated between year n and year n +1 was determined. The number of groups in category A in year n that remains in category A in year n+1, groups that were in category A in year n and deteriorate to condition categories B, C, D or F in year n +1 are recorded. This process is repeated for each condition category. The percent deterioration condition from each category to another is then determined. The average of deterioration condition rates for the groups for each condition transition group was used for the model.

In the deterioration transition matrix, the percent of deficient signs increases in the following year. Table I-10 shows the transition of sign group conditions in the deterioration model. For example, if a group of signs at year n is in condition A, then there is a 52 percent probability that at year n+1 the condition will remain A, 32 percent probability that more signs will become deficient and move the group to condition B, 8 percent probability that the group condition will become C, 3 percent probability that the group condition will become D, and 6 percent probability that the group condition will become F.

Table I-10. Sign deterioration condition transition matrix.

% from / to	A	B	C	D	F
A	52%	32%	8%	3%	6%
B		41%	34%	7%	17%
C			23%	42%	35%
D				7%	93%
F					100%

Table I-11 shows the increase of deficient signs in the deterioration model. For sign groups that are in condition A at year n and stay in this condition the next year, the increase in deficient signs is 1.3 percent. For sign groups that are condition A at year n and in the next year move to condition B, the increase in deficient signs is 4.2 percent. For sign groups that are in condition A at year n and the next year move to condition C, the increase in deficient signs is 8.9 percent. For sign groups that are in condition A at year n and in the next year move to condition D, the increase in deficient signs is 14 percent. For sign groups that are in condition A at year n and the next year move to condition F, the increase in deficient signs is 25.6 percent.

Table I-11. Increase of deficient signs in the sign condition deterioration model.

% from / to	A	B	C	D	F
A	+1.3%	+4.2%	+8.9%	+14.0%	+26.6%
B		+1.5%	+4.3%	+10.1%	+15.7%
C			+2.3%	+4.9%	+21.6%
D				+2.7%	+11.2%
F					+10.4%

e. For the improvement transition matrix, the number of sign groups that improve from year n to year n +1 is determined. The number of groups in category F in year n that remains in category F in year n+1, groups that

were in category F in Year n and in year n +1 improve to condition categories D, C, B or A in year n +1 are recorded. This process is repeated for each condition category. The percent improvement condition for each category to another is then determined. The average of improvement condition rates for the groups for each condition transition group was used for the general model.

In the improvement transition matrix, the percent of deficient signs decreases in the following year due to maintenance activities. Table I-12 shows the transition of sign group conditions in the improvement model. For example, if a group of signs is in condition B at year n and maintenance is applied to treat the deficient signs, then there is a 62 percent probability that the condition group will move to A in the next year, and 38 percent probability that the group will still remain in B.

Table I-12. Sign improvement condition transition model.

% from / to	A	B	C	D	F
A	100%				
B	62%	38%			
C	29%	59%	12%		
D	27%	29%	24%	20%	
F	12%	14%	14%	20%	41%

Table I-13 shows the decrease of deficient signs in the improvement model. For sign groups that are in condition B at year n and move to condition A in the next year, the decrease in deficient signs is 3.2 percent. For sign groups that are in condition B at year n and stay in condition B in the next year, the decrease in deficient signs is 1.4 percent.

Table I-13. Decrease of deficient signs in the sign condition improvement model.

% from / to	A	B	C	D	F
A	-1.1%				
B	-3.2%	-1.4%			
C	-9.0%	-5.0%	-2.1%		
D	-13.6%	-9.4%	-4.4%	-0.9%	
F	-36.3%	-23.1%	-24.6%	-10.8%	-11.8%

I.2.3 Perform the Needs Analysis

The needs analysis determines preservation activities and budget required to maintain the sign system in acceptable conditions. The model identifies the needs of maintenance and replacement of deficient signs over the analysis period. Needs are identified based on the signs condition and decision criteria as described in section I.1.3 Transition condition matrices are used to model the change in condition over time.

A random function is introduced into the model to incorporate the uncertainty expected in the condition transition process from year n to year n+1. The random function is based on the probabilities or likelihood of the condition transition from one condition to another, which was observed from the data. The deterioration and improvement matrix depicts the probability of percent increase (deterioration) or decrease (improvement) in defective signs within a group. Based on the resulting percentage of deficient signs at the end of the year (after deterioration or improvement), sign groups are assigned condition A, B, C, D, or F. End of the year n condition is the initial condition for year n+1.

Each condition category has associated a treatment. Sign groups in condition A receive "Do Nothing" treatment. For sign groups in condition B, the associated treatment is that 100 percent of defective signs receive maintenance. For sign groups in condition C, the associated treatment is that 60 percent defective signs receive

maintenance and 40 percent of defective signs are replaced. For sign groups in condition D, the associated treatment is that 20 percent defective signs receive maintenance and 80 percent of defective signs are replaced. For sign groups in condition F, the associated treatment is that 100 percent of defective signs are replaced. The cost of maintenance and replacement is based on UDOT average costs as shown in Table I-14.

Table I-14. Costs of preservation activities for highway signs.

Parameter	Value	Source
Cost of sign maintenance	$121	Average cost to maintain, UDOT data
Cost of sign replacement	$249	Average cost to replace, UDOT data

I.3 Step 3: Conduct Delayed Maintenance Scenarios Analyses

I.3.1 Formulate Delayed Maintenance Scenarios

Table I-15 describes the set of maintenance scenarios evaluated for the highway signs system. In Scenario 1, all needs, maintenance activities are performed with sufficient funds to implement the agency's preservation policy. The budget from this scenario is considered as the baseline budge. Scenario 2, "Do nothing," evaluates the impact of "no maintenance" on the future condition and budget needs of the highway sign system. Scenarios 3 and 4 model delayed maintenance either by policy or by limited budget. Delayed maintenance by policy is modeled by a delayed time cycle, therefore if a sign group needs maintenance in year n, then this activity is deferred by certain number of years. Delayed maintenance by limited budget is modeled by delayed maintenance until funds becomes available; priorities for funding are based on a priority maintenance index calculated as a multiplication of annual average daily traffic and number of signs in the group.

Table I-15. Key elements to analyze delayed maintenance scenarios for the highway sign system.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 10 years	Results
Signs Inventory Database with Inventory and Condition Assessment	Transition probability matrices to model the increase/ decrease of deficient signs	1. All Needs 2. Do Nothing. 3. Delayed Maintenance Maintenance treatments are delayed by a certain number of years: a. 1-year cyclical delay b. 3-year cyclical delay 4. Budget-driven with limited funds for maintenance. a. 80 percent of baseline budget b. 60 percent of baseline budget	Analytical Tools: Spreadsheet based model to forecast sign condition categories over the period of analysis Reports: • Impact on condition due to delayed maintenance. • Agency costs over time. • Changes in the sign system asset value and sustainability ratio.

Scenario 1 describes the situation of unlimited funding available and all treatments in the preservation plan are applied as needed. Scenario 2 is the opposite and all treatments are deferred while the sign system condition deteriorates over time. Scenario 3 shows the impact of delaying maintenance activities by 1 or 3 years. Scenario 4 shows the impact of a budget limited to 60 percent or 80 percent of the baseline budget.

In the budget-driven scenario (Scenario 4), sign groups are ranked by a Maintenance Priority Index, which is based on traffic volume and location. The Dynamic Bubble-Up (DBU) method is used to allocate funds beginning with the sign group with the highest MPI until funds are exhausted (Chang 2007). Highway agencies may use different criteria and/or method to prioritize funding allocation. Sign groups in need of a maintenance

or replacement, but delayed due to limited budget, are moved to a lower condition category. The transition matrices based on probabilities are used for deterioration or improvement.

I.3.2 Perform the Delayed Maintenance Scenarios Analyses

Table I-16 shows the results of the scenarios analyses including the total agency costs in 10 years, backlog at the end of analysis, and the percentage of sign groups that have more than 20 percent deficient signs.

Table I-16. Summary of the scenario analyses results for signs.

Scenario	Description	Total Agency Cost[1]	Backlog Cost[1]	Percentage of Sign Groups with More than 20 percent Signs Deficient (Condition F)[1]
1	All Needs	$7.8 M	$0	1
2	Do Nothing	$0 M	$97.2 M	100
3	Delayed maintenance			
	a. 1-year cyclical delay	$13.5 M	$7.8 M	18
	b. 3- year cyclical delay	$17.3 M	$42.1 M	92
4	Budget-driven with limited funds			
	a. 80 percent of baseline budget	$6.2 M	$17.1 M	19
	b. 60 percent of baseline budget	$4.6 M	$30.4 M	40

[1]At the end of year 10.

At the beginning of the analysis, the percentage of groups in condition F, with more than 20 percent signs deficient, is 15 percent. In Scenario 1, the percentage of deficient signs reduces to 1 percent with an investment of $7.8 million over a 10-year period.

In Scenario 2, "Do nothing," no funding is available and the backlog cost increases to $97.2 million and 100 percent of the system reaches condition F at the end of the year 10.

In scenarios 3a and 3b, the agency costs increase due to delayed maintenance in comparison to Scenario 1. In Scenario 3a, maintenance activities delayed by 1 year, agency costs are $13.5 million and $7.8 million is backlogged, then 18 percent of the system is in condition F at the end of year 10. In Scenario 3b, maintenance activities delayed by 3 years, agency costs are $17.3 million and $42.1 million is backlogged, then 92 percent of the system is in condition F at the end of year 10.

In Scenario 4a, maintenance activities are delayed due to limited budget (80 percent of baseline budget), agency costs are $6.2 million and $17.1 million is backlogged, then 19 percent of the system is in condition F at the end of year 10. In Scenario 4b, maintenance activities are delayed due to limited budget (60 percent of baseline budget), agency costs are $4.6 million and $30.4 million is backlogged, then 40 percent of the system in condition F at the end of year 10.

I.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.

Consequences on the Sign System Condition

At the beginning of the analysis, 42 percent of the highway system in category A, and 15 percent in category F as Figure I-3 shows.

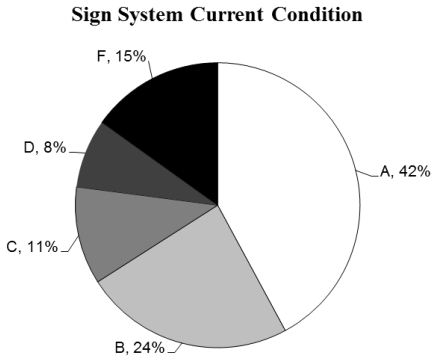


Figure I-3. Sign system current condition.

Figure I-4 shows the distribution of sign categories at the end of year 10. In Scenario 1, all needs, there are only 1 percent sign groups in condition F. In Scenario 2, "Do nothing," 100 percent of the sign groups fall into category F. In scenarios 3a and 3b, the sign groups in category F increases to 18 percent and 92 percent respectively. Scenario 4a, 80 percent of baseline budget, shows a similar condition as Scenario 3a, but it results in less the sign groups in condition A. Scenario 4b, 60 percent of baseline budget, ends up with 40 percent of the sign groups in condition category F, and 28 percent in condition category A.

Figure I-4. Sign condition categories at the end of the analysis period, 10 years.

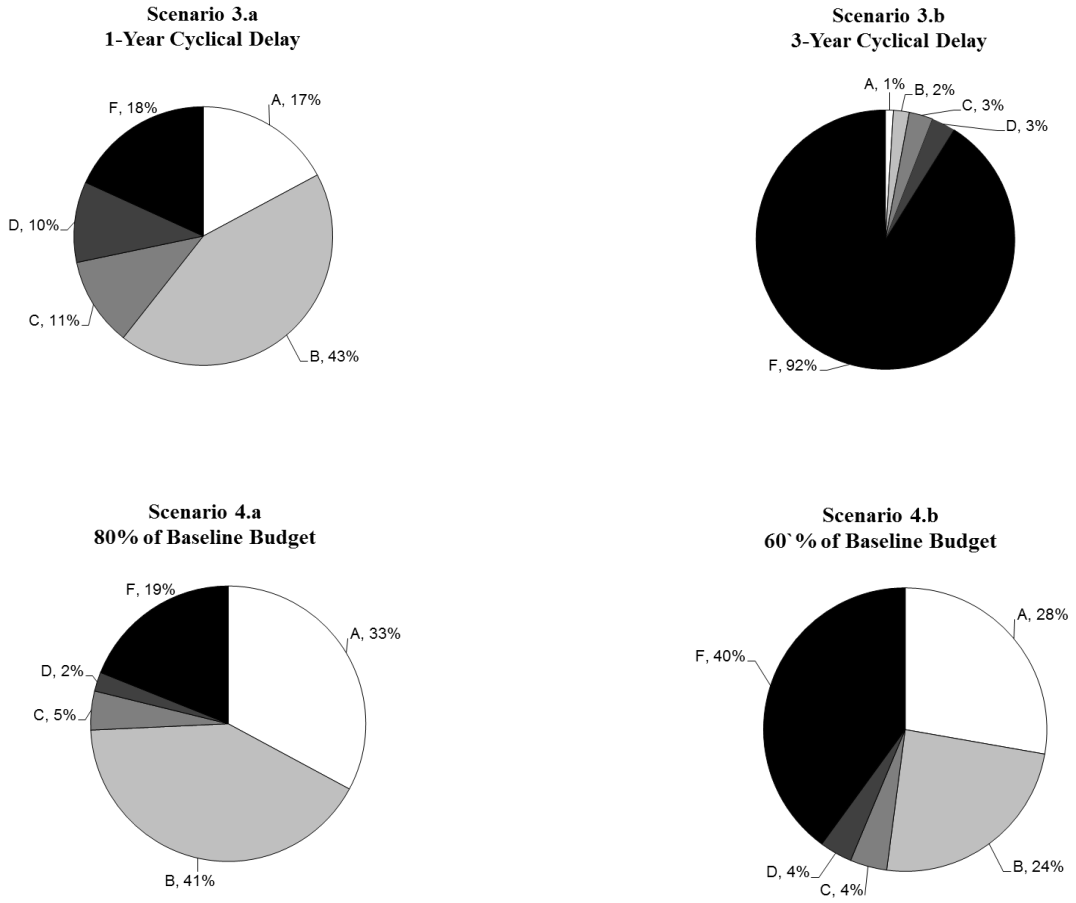


Figure I-4. Sign condition categories at the end of the analysis period, 10 years. (Continued)

Figure I-5 shows the changes in condition categories over time under the different scenarios. Only in Scenario 1 the percentage of sign groups in condition A improves during the analysis period. In Scenario 2, there are no signs in condition category A at the end of year 3, and all groups are in condition category F at the end of year 7. Scenario 3a, delayed maintenance activities by 1 year, has a negative impact on the percentage of sign groups in condition category A, while the number of groups in other condition categories increases. In scenario 3b, the 3 years delayed of maintenance activities has a significant impact on the condition of the sign system with the majority of sign groups in condition category F after year 2. Scenarios 4a and 4b result with the majority of sign groups in condition category A or B, but the number of groups in condition category F also increases.

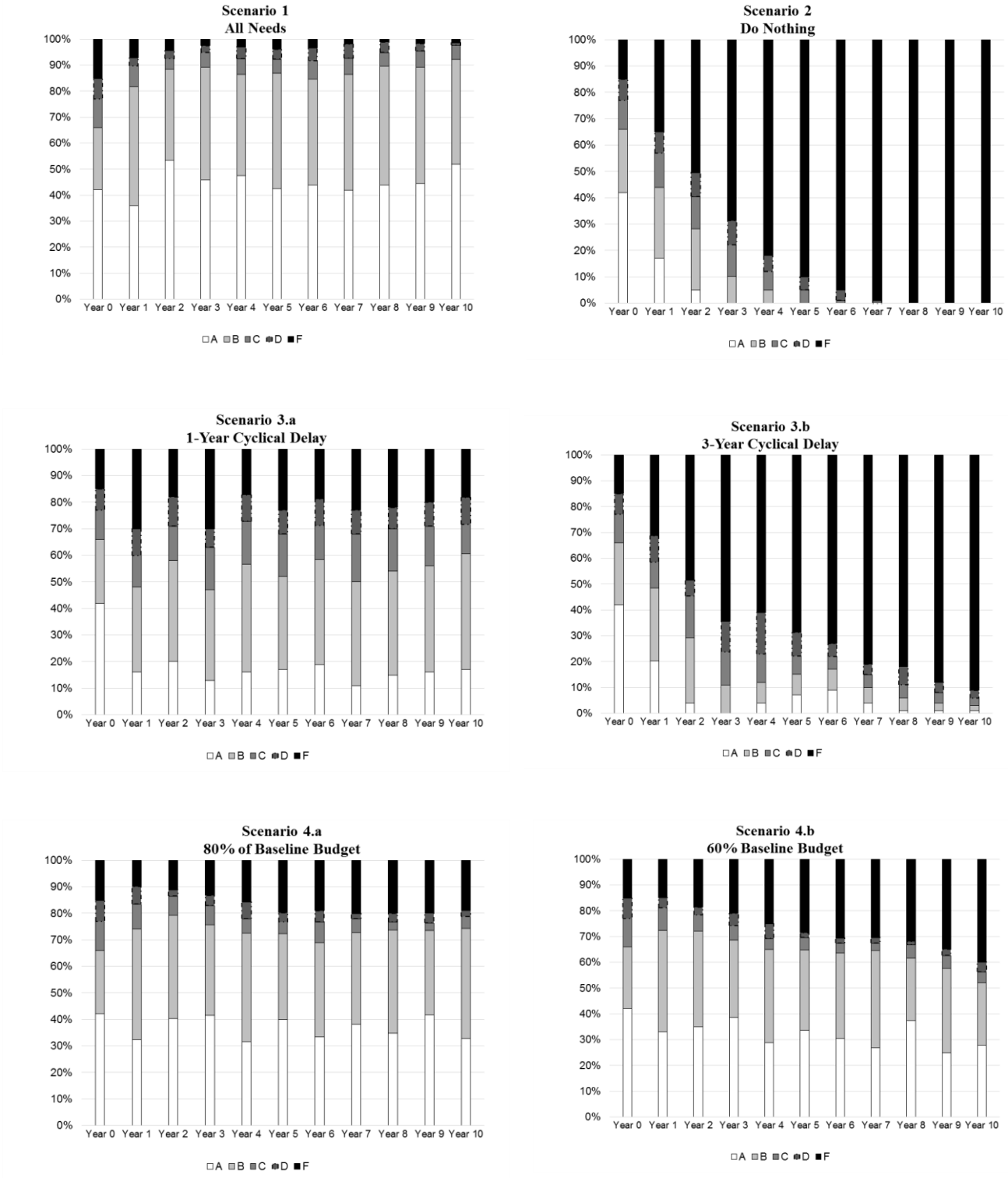
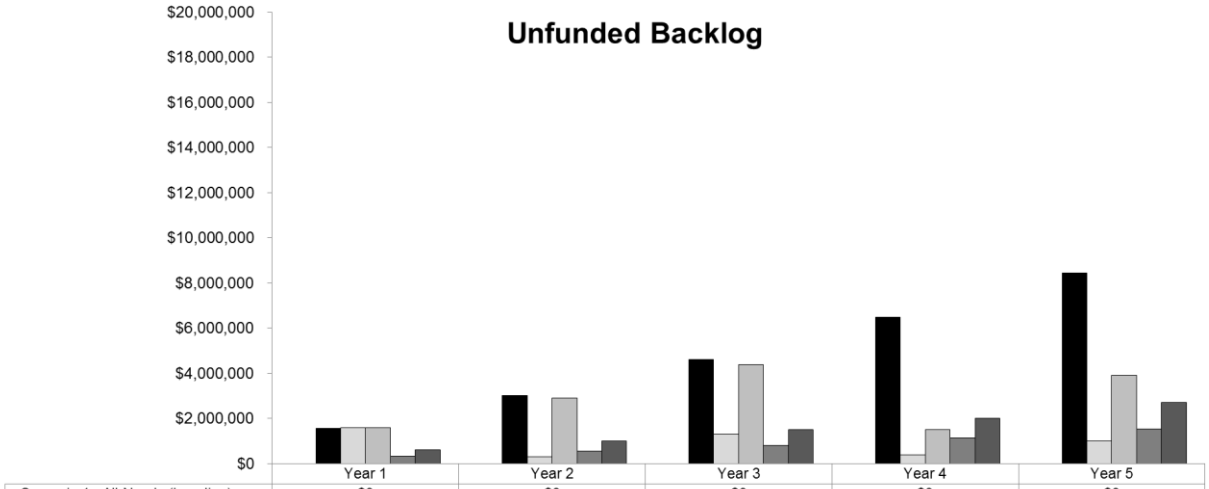


Figure I-5. Sign condition categories over time, 10 years.

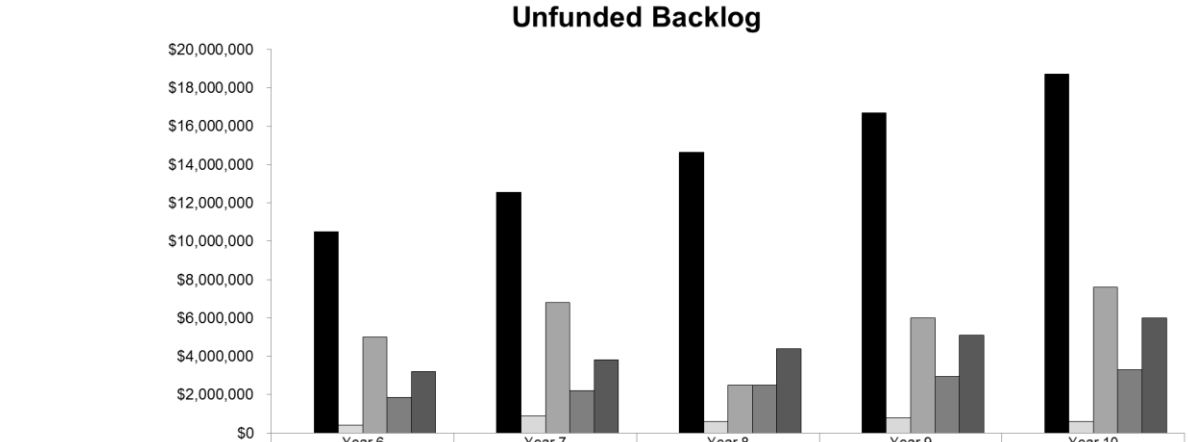
Consequences on Future Budget Needs

If maintenance activities are delayed, not only the sign system condition deteriorates and system value goes down, but also unfunded backlog accumulates. Figures I-6 and I-7 show the unfunded backlog over time which is $0 for Scenario 1, all needs, and increases to $18.73 million for Scenario 2, "Do nothing." Scenario 3b, "Delayed maintenance by 3 years," has the second highest backlog, reaching $7.6 million at year 10; followed by Scenario 4b, "60 percent of baseline budget," in which the backlog reaches $6.0 million. The backlog costs under Scenario 3a, "Delayed maintenance by 1 year," ranges between $0.3 and $1.6 million, while Scenario 4a, "80 percent of baseline budget," increases from $0.3 million to $3.3 million in 10 years.



	Year 1	Year 2	Year 3	Year 4	Year 5
Scenario 1 - All Needs (baseline)	$0	$0	$0	$0	$0
Scenario 2 - Do Nothing	$1,567,917	$3,028,745	$4,615,466	$6,493,304	$8,453,345
Scenario 3.a - 1-Year Cyclical Delay	$1,600,000	$300,000	$1,300,000	$400,000	$1,000,000
Scenario 3.b - 3-Year Cyclical Delay	$1,600,000	$2,900,000	$4,400,000	$1,500,000	$3,900,000
Scenario 4.a - 80% of Baseline Budget	$318,080	$548,248	$800,092	$1,142,625	$1,536,079
Scenario 4.b - 60% of Baseline Budget	$600,000	$1,000,000	$1,500,000	$2,000,000	$2,700,000

Figure I-6. Unfunded backlog for maintenance scenarios, years 1 through 5.

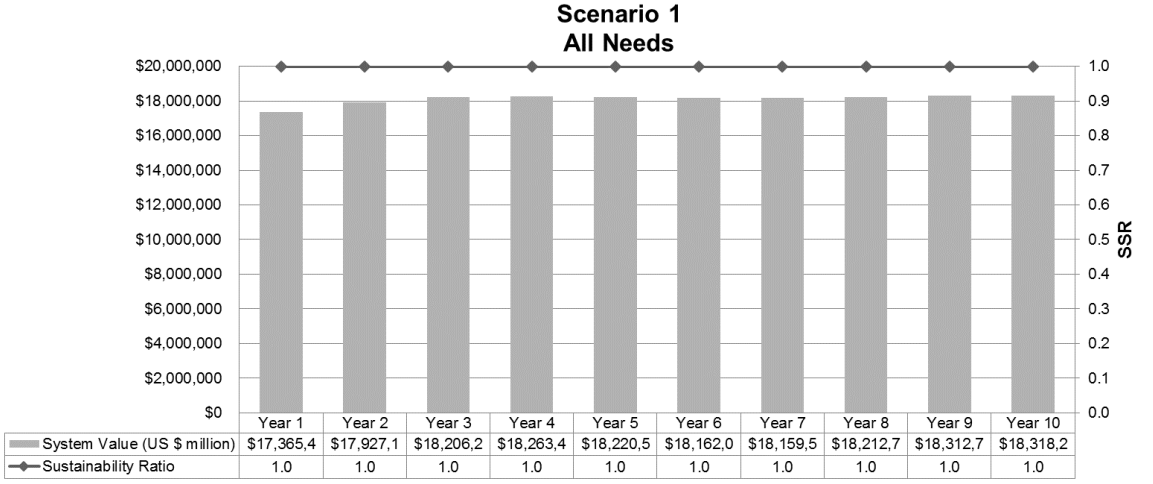


	Year 6	Year 7	Year 8	Year 9	Year 10
Scenario 1 - All Needs (baseline)	$0	$0	$0	$0	$0
Scenario 2 - Do Nothing	$10,502,079	$12,542,235	$14,630,163	$16,682,640	$18,732,107
Scenario 3.a - 1-Year Cyclical Delay	$400,000	$900,000	$600,000	$800,000	$600,000
Scenario 3.b - 3-Year Cyclical Delay	$5,000,000	$6,800,000	$2,500,000	$6,000,000	$7,600,000
Scenario 4.a - 80% of Baseline Budget	$1,839,074	$2,197,346	$2,512,336	$2,955,887	$3,294,597
Scenario 4.b - 60% of Baseline Budget	$3,200,000	$3,800,000	$4,400,000	$5,100,000	$6,000,000

Figure I-7. Unfunded backlog for maintenance scenarios, years 6 through 10.

Figure I-8 shows changes of the sign system value together with the sign sustainability ratio (SSR) over the analysis period of 10 years. SSR indicates on a scale 0 to 1 the percentage of asset needs that are funded each year.

In Scenario 1, where all needed maintenance activities are funded, the SSR is 1. On the other hand, in Scenario 2, "Do nothing," where no treatments are performed, the SSR is 0 during the analysis period. For delayed maintenance scenarios 3a and 3b, the SSR decreases significantly in those years when maintenance is delayed. In the budget-driven scenarios 4a and 4b, the SSR is continuously declining as a result of limited funding. The largest decrease in the sign system value is observed in Scenario 2, "Do nothing," followed by Scenario 3b, "Delayed maintenance by 3 years," and Scenario 4b, "60 percent of baseline budget."



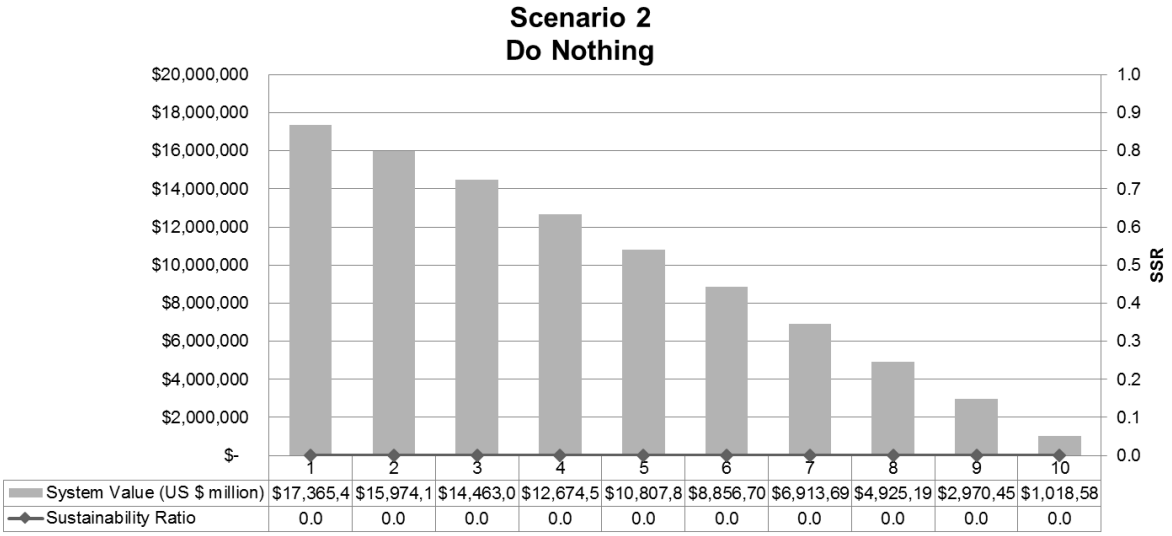
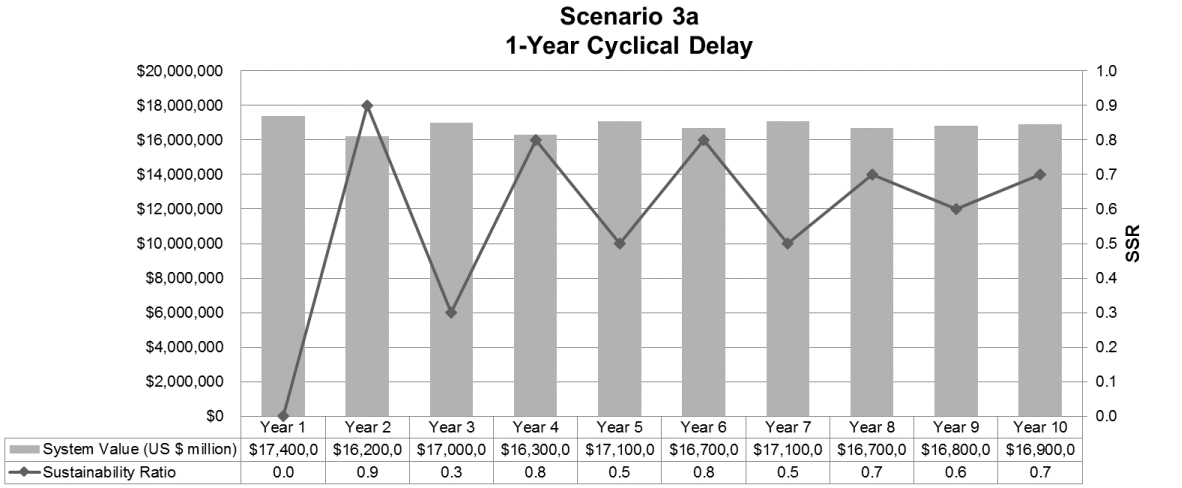
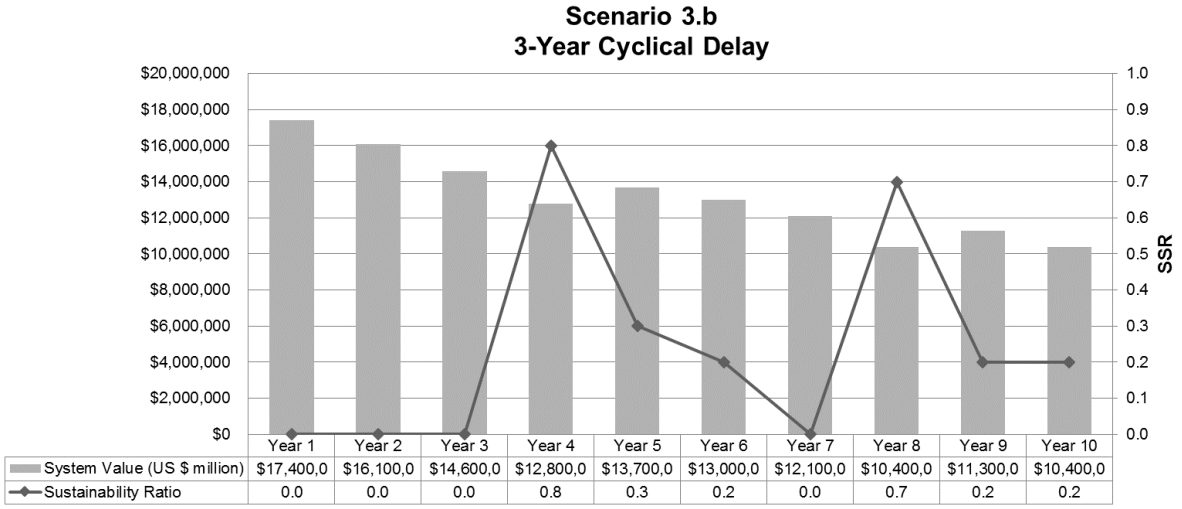


Figure I-8. Sign system value and sustainability ratio.





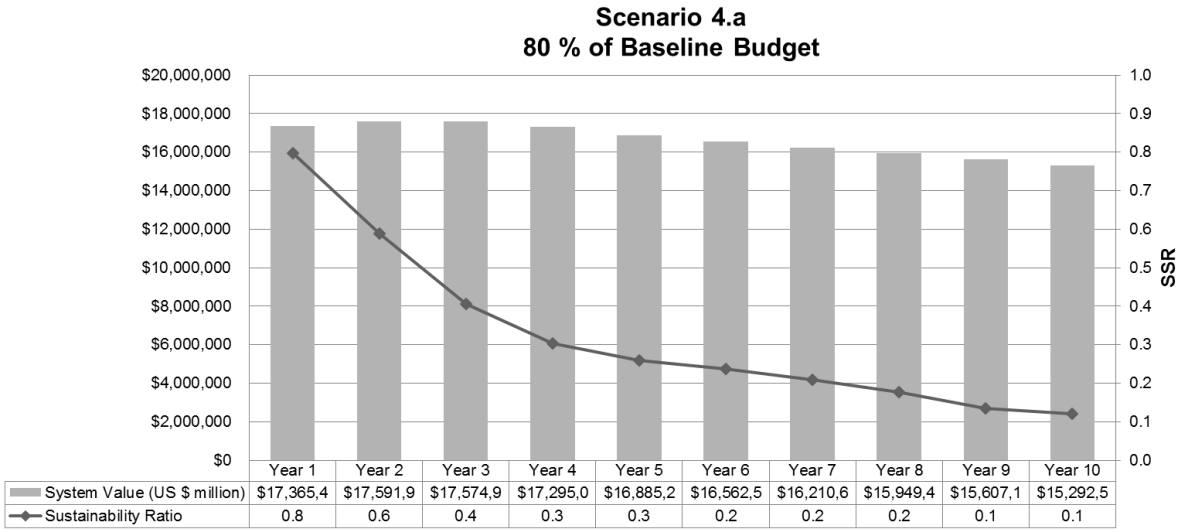


Figure I-8. Sign system value and sustainability ratio. (Continued)

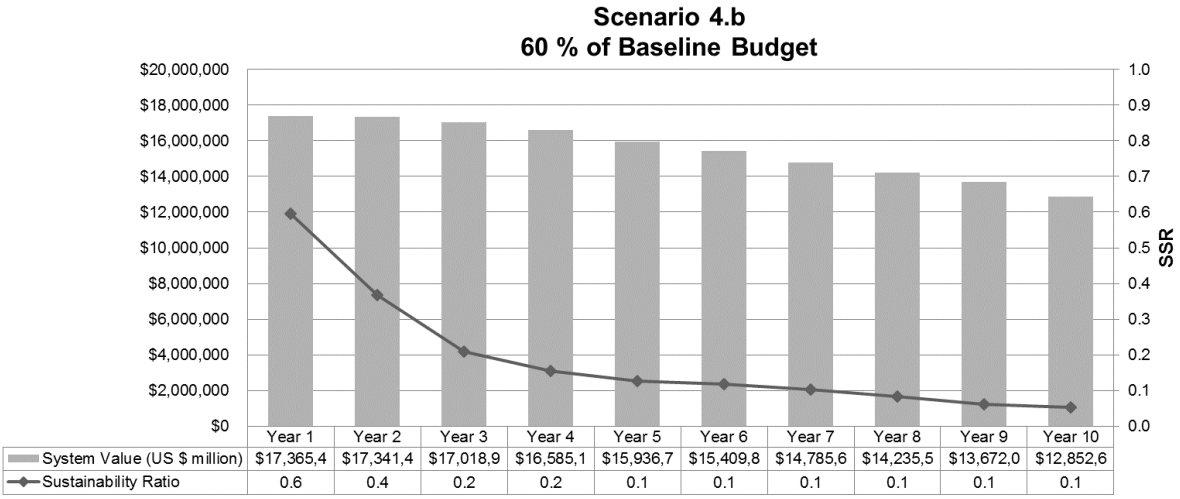


Figure I-8. Sign system value and sustainability ratio. (Continued)

I.4 Summary

The scenario results that were summarized in Table I-16 demonstrate the effects of delaying maintenance to signs. Delaying maintenance activities results in increased needs over time and increased numbers of signs in condition category F. Specific results for the case study include the following:

- In Scenario 1, "All needs," results in agency costs of $7.8 million or total agency costs, a sign system in good condition (52 percent in condition category A, and 40 percent in condition category B), no backlog costs, and a system value of $18.3 million.
- In Scenario 2, "Do nothing," results in $18.7 million backlog costs, and 100 percent of signs in poor condition (condition Category F) at the end of the 10 years.
- Scenario 3a, "Delayed maintenance activities by 1 year," increases the agency costs to $13.5 million, while results in a significant increase in the percent of signs in condition F (ranging between 17 percent and 30 percent) during the analysis period. Scenario 4a, "80 percent of the baseline budget," shows similar results.
- Scenario 3b, "Delayed maintenance activities by 3 years," best illustrates the effects of delaying all investments on signs. In this case, agency costs are increased from $7.8 to $17.3 million and the percent of signs in poor condition increases to 92 percent at the end of 10 years.
- Scenario 4b, "40 percent of baseline budget," illustrates that a cut in the budget reduces spending to $4.6 million, at the cost of worsened the sign system codition condition (40 percent in condition F at the end of analysis) and a $6 million backlog.

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