APPENDIX H

Procedure to Quantify Consequences of Delayed Maintenance of Pavement Markings

The purpose of pavement markings is to provide “guidance and information for the road user” for safer driving conditions (FHWA 2009). Longitudinal lane, shoulder, and center lines; raised markers; and symbols, guidance, and warning messages found on the surface of the roadway, all fall under the pavement marking category. Federal Highway Administration has recognized the positive effects of pavement markings, also called roadway delineation, on roadway safety since 1983 with the implementation of the pavement marking initiatives (Migletz et al. 1994). Pavement markings are especially important during nighttime when fatal crashes occur twice more often than during daytime (NHTSA 2014). Delaying maintenance of the pavement markings system will not only impact the agency’s future maintenance and replacement costs but it will also affect safety by increasing the likelihood of car accidents. Figure H-1 shows the procedure to quantify the consequences of delayed maintenance of pavement markings systems.

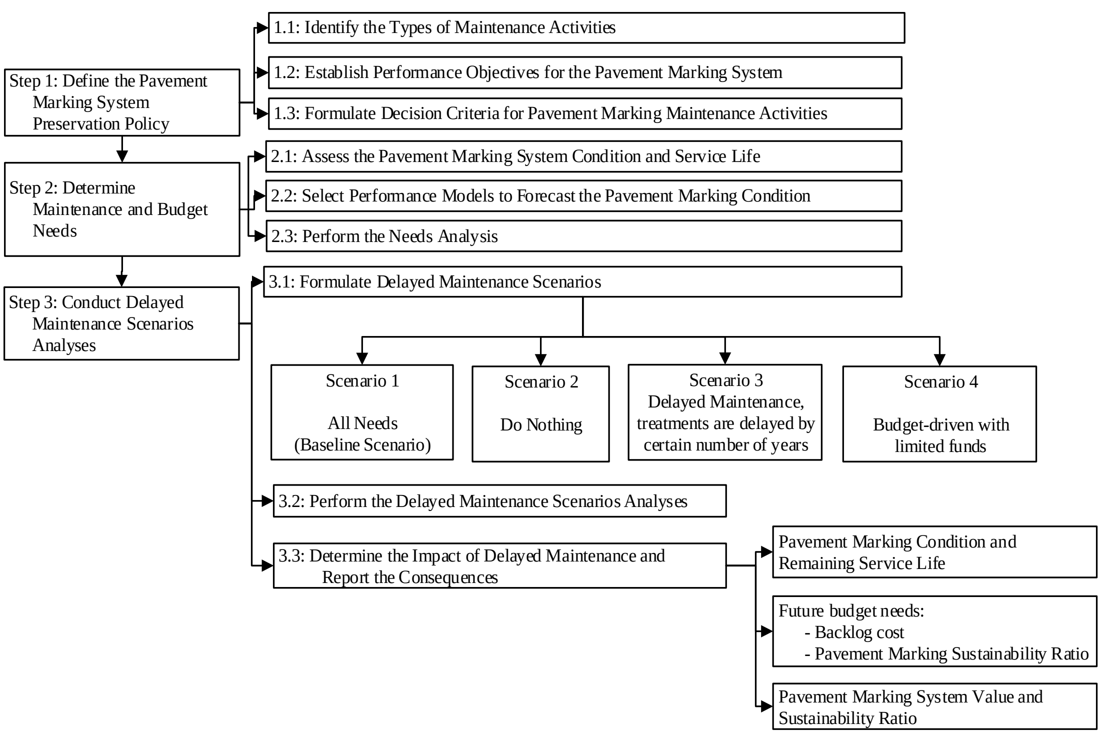


Figure H-1. Procedure to quantify the consequences of delayed maintenance of pavement markings.

H.1 Step 1: Define the Pavement Marking System Preservation Policy

The preservation policy for the pavement marking system is usually formulated by a central office that provides policies for maintenance, specifications for materials, and criteria to allocate funding. FHWA has also established standards in the MUTCD regarding minimum reflectivity requirements for pavement markings.

H.1.1 Identify the Types of Maintenance Activities

Among all agencies, the primary type of maintenance for pavement markings is routine or corrective depending on the type of material. Frequently used materials for pavement markings are waterborne paint, epoxy, and thermoplastic. Other materials used for pavement markings include polymethyl methacrylate, polyester, and tape. (Migletz et al. 2001). These materials can be classified in two main types: nondurable and durable. Nondurable pavement markings (e.g., water based, latex based, oil based, etc.) are restriped routinely while durable pavement markings (e.g., epoxy, thermoplastic, raised reflective markings, etc.) are typically maintained based on their condition. Some regions are in the process of converting their nondurable pavement markings to long life pavement markings as the long life markings are expected to be more cost efficient based on life cycle cost analysis.

Routine maintenance includes activities that are performed on a routine basis to preserve the level of service of the pavement marking system. Corrective maintenance activities include repairs and replacement of individual elements. The decision to replace a pavement marking is mainly condition-driven, but it can also occur when there is a change in design requirements, for example during the process of relocating lanes or reconfiguring intersections or changes in standards.

H.1.2 Establish Performance Objectives for the Pavement Marking System

In this step, the agency should select the set of performance measures that will be used to show the effects of delaying maintenance. Pavement marking standards, warrants and design criteria are described in The Manual on Uniform Traffic Control Devices (MUTCD) and additional information can be found in the FHWA Roadway Delineation Practices handbook (Migletz et al. 1994). Typically, pavement markings are assessed for retroreflectivity following the MUTCD standards. (Markow 2007), and can be categorized into three general groups:

- “**Not required to be retroreflective:** These are pavement markings where ambient illumination assures adequate visibility or pavement markings that are needed only in the daytime (e.g., where access to a park may be daytime only). These pavement markings do not require minimum levels of retroreflectivity.” (FHWA 2010)
- **“Required to be retroreflective**, but not subject to minimum levels: All markings other than those discussed in the first bullet must be retroreflective, but some of these markings are not subject to the new minimum retroreflectivity levels. Examples of exceptions provided by the new MUTCD language include crosswalk markings, other transverse markings, words, symbols, arrows, etc. Some longitudinal lines are exempt from the new minimum retroreflectivity levels under certain conditions, such as presence of continuous roadway lighting or raised retroreflective pavement markers. […] Pavement markings on Interstate Highways are required to be retroreflective” (FHWA 2010).
- **“Subject to minimum retroreflectivity levels:** These include the white and yellow longitudinal pavement markings that are required or recommended in the MUTCD, such as the center lines, edge lines, lane lines, and channelizing lines that the MUTCD says shall or should be used above certain volumes or for certain roadway conditions.” (FHWA 2010) The minimum levels of retroreflectivity for certain pavement markings are defined in MUTCD based on roadway type, posted speed, and weather conditions. “During winter months in northern climates, along some isolated horizontal curves, [or] near driveways” (FHWA 2010) the minimum retroreflectivity levels may not be reached.

Table H-1 shows the minimum retroreflectivity levels recommended by FHWA for pavement markings. However, minimum initial and in-service retroreflectivity requirements differ among states as the National Cooperative Highway Research Program NCHRP Document 92 (Bahar et al. 2006) shows in Table H-2.

Table H-1. Minimum maintained retroreflectivity levels for longitudinal pavement markings.

	Posted Speed (mph)		
	≤ 30	35 - 50	≥ 55
Two-Lane roads with centerline markings only	n/a	100 $mcd/m^2/lux$	250 $mcd/m^2/lux$
All other roads	n/a	50 $mcd/m^2/lux$	100 $mcd/m^2/lux$

Source: FHWA 2010

Table H-2. Minimum initial and in-service pavement marking retroreflectivity required by states.

Type of line	Standard color of line	Material type	Minimum Retro reflectivity Requirements ($mcd/m^2/lux$)[3]																
			CA	IL	IA	KA	MD	MI	MN	MO	NV	NJ	NY	NC	OH	OR	PA	TX	UT
Centerline	Yellow	Paint	-		200 (100)	(100)	150	(140–160)	180 (80)	225	275 (125)	N/A	N/A	-	N/A	-	200 (125)	175	N/A
		Thermo	150		-	275 (100)	150	(140–160)	500 (80)	225	-	N/A	N/A	250 (100-150)	N/A	200 (125)	250 (200)	250	N/A
		Epoxy	150		-	275 (100)	-	-	200 (80)	225	275 (125)	N/A	N/A	250	N/A	200 (125)	250 (175)	-	N/A
Edgeline	Yellow	Paint	-		200 (100)	(100)	150	(130-165)	180 (80)	225	275 (125)	N/A	N/A	-	N/A	-	200 (175)	175	N/A
		Thermo	150		-	275 (100)	150	(130-165)	500 (80)	225	-	N/A	N/A	250 (100-150)	N/A	200 (125)	200 (175)	125	N/A
		Epoxy	150		-	275 (100)	-	-	200 (80)	225	275 (125)	N/A	N/A	250	N/A	200 (125)	250 (200)	-	N/A
	White	Paint	-		300 (150)	(150)	250	(220-270)	180 (80)	300	375 (125)	N/A	N/A	-	N/A	-	250 (175)	-	N/A
		Thermo	250		-	(150)	250	(220-270)	500 (80)	300	-	N/A	N/A	375 (150)	N/A	250 (150)	250 (175)	-	N/A
Lane Line/Skip Lines	White	Paint	-		300 (150)	(150)	250	(240-260)	275 (80)	300	375 (125)	N/A	N/A	-	N/A	-	300 (250)	-	N/A
		Thermo	250		-	325 (150)	250	(240-260)	700 (80)	300	-	N/A	N/A	375 (100-150)	N/A	250 (150)	300 (250)	-	N/A
		Epoxy	250		-	325 (150)	-	-	300 (80)	300	375 (125)	N/A	N/A	375	N/A	250 (150)	300 (225)	-	N/A

Note: minimum in-service specifications are in parenthesis

Source: Bahar et al. 2006

In selecting performance measures for pavement markings, it is important to consider the different causes of failure, such as "loss of substance by abrasive wear on the upper surface, cohesive failure of the paint (within the paint layer), and/or adhesive failure at the interface with the concrete substrate" (Migletz et al. 1994). Factors affecting pavement marking performance are divided in two main groups, visibility factors and durability factors, as Table H-3 shows (Benz et al. 2009).

Table H-3. Pavement marking performance factors.

Visibility factors	Durability Factors
Contrast, Retroreflectivity, Presence, Pavement Texture, Pavement Color, Marking Color, Marking Type, Marking Size, Headlamp Type, Viewing Geometry, Ambient Lighting Conditions	Marking Material, Marking Thickness, Pavement Type, Pavement Texture, Traffic Volume, Weather, Maintenance Activities Marking Location (Edgeline, Centerline, Lane line) Roadway Geometry (Horizontal Curves, Weaving Areas, etc.

Source: Benz et al. 2009

Pavement markings performance categories with corresponding data and contributing factors are shown in Table H-4 (e.g., brightness, day visibility, retroreflectivity).

Table H-4. Pavement marking performance categories and important contributing factors.

Category	Important Data or Factor	Source
Overall Performance	Brightness Benefit Factor (BBF) = average retroreflectivity over anticipated service life * service life / average cost per unit length	(KDOT 2002)
Condition	Day Visibility (Presence)	NCHRP Synthesis 470 (Zimmerman 2015)
	Retroreflectivity threshold of min. 100 mcd/m^2/lux	(Kopf 2004)
	Durability, Appearance, Nighttime Visibility – each rated on a scale 0 (none remaining) to 10 (perfect)	(Migletz et al. 1994)

Individual performance measures and factors affecting pavement markings system performance can be tied to levels of service using a simplified scale. For example, CDOT's inspection guidelines rate the visibility of pavement markings. The rating ranges from 4 when 81-100 percent of pavement markings are visible, to 0 when 0-20 percent of pavement markings are visible. There is also a condition indicator rating for retroreflectivity reading (mcd/m^2/lux), which ranges from a rating of 4 when it is greater than 200 mcd/m^2/lux, to rating of 0 when it is 49 mcd/m^2/lux or less. Annual inspections are performed on 700 different random locations statewide. These ratings are used to assign a letter grade from A to F for the Maintenance Level of Service (MLOS) to define pavement markings categories. The MLOS grade is used as a base line for the current system performance, and to set target objectives for future years. CDOT uses the levels of service for stripping and markings shown in Table H-5. The criterion is based on the percentage of striping and markings that are not functioning as intended (worn or not easily visible).

Targets for maintenance depend upon the performance measures used by the agency and data availability. The following common performance measures are used in pavement markings to setup targets (Markow 2007):

- Loss of retroreflectivity
- Pavement marking age and estimated remaining life
- Percentage of pavement markings at certain level of service
- Percentage of broken or missing raised pavement markers
- Deterioration due to abrasion or wear
- Customer complaints.

The performance measures can be either physical (measured in units, e.g., mcd/m2/lux for retroreflectivity), or qualitative (assessed on a scale: e.g., good, fair, poor; A, B, C, D, F) (Markow 2007). The pavement marking model developed in this research considers level of service categories (A, B, C, D, F) based on retroreflectivity measurements or remaining service life, and captures the percentage of the system in each category due to a given maintenance preservation policy. Retroreflectivity thresholds for the condition categories are shown in Table H-6 based on the data shown in Table H-2.

Table H-5. Levels of service for pavement striping and markings.

Maintenance Program Area: Traffic Services	**Survey Item:** Striping, Markings
Pavement striping and other markings are in generally excellent condition, with a high visibility and reflectivity in daytime and nighttime, and little or no wearing and obliteration. Approximate limits for levels of service are as follows, expressed as a percent of striping and other pavement markings that are worn or not easily visible: A+, less than 5.0 percent; A, up to 9.2 percent; A-, up to 13.3 percent.	
Pavement striping and other markings are in generally good condition, visible in daytime and nighttime, and showing only minor wearing or obliteration. Approximate limits for levels of service are as follows, expressed as a percent of striping and other pavement markings that are worn or not easily visible: B+, up to 17.5 percent; B, up to 22.5 percent; B-, up to 27.5 percent.	
Pavement striping and other markings are in fair condition, generally visible in daytime and nighttime, but with noticeable wearing and obliteration, or loss of reflectivity. Approximate limits for levels of service are as follows, expressed as a percent of striping and other pavement markings that are worn or not easily visible: C+, up to 32.5 percent; C, up to 36.7 percent; C-, up to 40.7 percent.	
Pavement striping and other markings are in marginal condition, with noticeable wearing, obliteration, or loss of reflectivity in almost half of the markings. Approximate limits for levels of service are as follows, expressed as a percent of striping and other pavement markings that are worn or not easily visible: D+, up to 45.0 percent; D, up to 48.3 percent; D-, up to 54.7 percent.	
Pavement striping and markings are essentially worn and obliterated. Markings that are still present are not easily visible. Approximate limits for levels of service are as follows, expressed as a percent of striping and other pavement markings that are worn or not easily visible: F+, up to 55.0 percent; F, up to 75.0 percent; F-, more than 75.0 percent.	

Source: CDOT 1999

Table H-6. Pavement marking condition categories based on retroreflectivity.

Condition Category	Lower Retroreflectivity Limit
A	319 mcd/m²/lux
B	263 mcd/m²/lux
C	207 mcd/m²/lux
D	150 mcd/m²/lux
F	below 150 mcd/m²/lux

The inventory used in the example includes pavement markings with three types of materials (epoxy, polyurea, and thermoplastic), and two colors (white, yellow). The model predicts the percentage of pavement markings in each condition level category. Pavement markings below 150 mcd/m²/lux are scheduled for repainting in order to restore the retroreflectivity to its initial value of 375 mcd/m²/lux as mandated by FHWA. In the model, the user specifies whether the analysis is condition based or age based, and the available budget over the period of analysis. The model calculates the budget needs over the analysis period for repainting pavement markings with retroreflectivity vales below 150 mcd/m²/lux.

H.1.3 Formulate Decision Criteria for Pavement Marking Maintenance Activities

This step involves determining what maintenance activities should be included in the pavement markings preservation program. Maintenance activities include cleaning, repainting or reapplying, repairing or replacing, or removal. Maintenance activities for pavement markings are recommended to be scheduled in coordination with pavement treatment activities needed in the same road segment (AASHTO 2007).

The criteria for maintenance activities depends on the preservation policy and the performance measures selected by the agency. Most of the maintenance activities are formulated based on field surveys to determine the pavement marking condition. For example, in Minnesota, each district has a stripping coordinator. Some districts rely on retroreflectometer data and others on visual inspection to determine maintenance needs for the following year. The districts decide whether latex or epoxy paint is used to refresh the markings. Epoxy paint last about three years, while latex paint is expected to last one year. The type of paint depends on the ADT and pavement surface type. At North Carolina Department of Transportation, pavement markings are checked for location and visibility with annual inspections. The inspections are performed on a representative sample. Routine maintenance is performed for nondurable pavement markings and they are typically restriped twice a year. Maintenance activities affected by a resurfacing cycle or snowplowing are considered routine.

Durable pavement markings are replaced based on condition. Currently, the types of pavement markings used in North Carolina include paint, thermoplastic, cold applied plastic, and polyurea. Colorado Department of Transportation annually inspects a random sample of pavement marking assets. The condition ratings from the inspections are then used to formulate the budget. In Utah, pavement markings are also inspected semiannually, where a representative sample is measured for retroreflectivity. The regions have full authority over maintenance activities. Maintenance for water-based (less durable) pavement markings is considered routine maintenance and they are repainted annually. More durable markings (e.g., epoxy paint) are maintained based on performance. The MMQA (Maintenance Management Quality Assurance) rating is related to nighttime visibility of the lines. The results from semiannual inspection is used to identify the percent of assets which are deficient within a station (section of highway). Based on this percentage, the station is given a Level of Maintenance (LOM) category which is expressed with a letter grade (i.e., A, B, C, D, and F) and a target grade (A to C) is established for each maintenance activity. “Once a target LOM is established, the goal is to meet that LOM as closely as possible, neither falling short of the target nor exceeding it” (UDOT 2012).

Florida Department of Transportation determines all pavement markings that fall below their standard for visibility through their annual inspection process. Stripping that does not meet the MRP standard is scheduled to be restriped. At the project level, Florida’s MRP handbook specifies maintenance conditions for pavement markings. During inspections, each line is evaluated per the MRP standard to determine if maintenance is needed. For example, striping does not meet the MRP standards when the following conditions exist.

1. If more than 10 percent of the length of any line is less than 5.4 inches wide during daylight inspection.
2. If more than 10 percent of the length and width of any line is not visible for a distance of 160 feet at night.
3. If more than 10 percent of the length of any line is missing.
4. If more than 10 percent of the length of any line is covered by soil, grass, or debris.

In this study, the decision criteria for maintenance activities is based on minimum retroreflectivity standards in terms of a letter grade system. “Paint” is applied when a pavement marking reaches category D or F to restore the retroreflectivity level.

H.2 Step 2: Determine Maintenance and Budget Needs for the Pavement Marking System

H.2.1 Assess the Pavement Marking System Condition

The MUTCD provides general guidelines on the condition assessment for pavement markings. Visual inspections using retroreflectometers (handheld or mobile) are performed at daytime and nighttime (FHWA 2009). New MUTCD mentions the following condition assessment methods:

"**Calibrated Visual Nighttime Inspection:** Prior to conducting a nighttime inspection from a moving vehicle and in conditions similar to nighttime field conditions, a trained inspector calibrates his eyes to pavement markings with known retroreflectivity levels at or above those in Table 3A-1. Pavement markings identified by the inspector to have retroreflectivity below the minimum levels are replaced." (FHWA 2010)

"Consistent Parameters Visual Nighttime Inspection: A trained inspector at least 60 years old conducts a nighttime inspection from a moving vehicle under parameters consistent with the supporting research. Pavement markings identified by the inspector to have retroreflectivity below the minimum levels are replaced" (FHWA 2010)

"Measured Retroreflectivity: Pavement marking retroreflectivity is measured using a retroreflectometer. Pavement markings with retroreflectivity levels below the minimums are replaced." (FHWA 2010)

"Service Life Based on Monitored Markings: Markings are replaced based on the monitored performance of similar in-service markings with similar placement characteristics. All pavement markings in a group/area/corridor are replaced when those in the representative monitored control set are near or at minimum retroreflectivity levels. The control set markings are monitored on a regular basis by the visual nighttime inspection method, the measured retroreflectivity method, or both" (FHWA 2010)

"Blanket Replacement – All pavement markings in a group/area/corridor or of a given type are replaced at specific intervals. The replacement interval is based on when the shortest-life material in that group/area/corridor approaches the minimum retroreflectivity level. The interval is also based on historical retroreflectivity data for that group/area/corridor." (FHWA 2010)

"Other Methods – Other methods developed based on engineering studies that determine when markings are to be replaced based on the minimum levels in Table 3A-1." (FHWA 2010)

Pavement marking durability and retroreflectivity is affected by several factors, including wet thickness of paint during application. A report for Missouri DOT suggests that "new pavement surfaces should receive a heavier one-time application of material or be striped twice in a season" (Weinkein et al. 2002). Also the color of the marking is a factor, as yellow markings tend to deteriorate twice as fast as white markings (Sarasua et al. 2012). The pavement type also affects the pavement marking deterioration rate, usually paint lasts longer on asphalt than on concrete. Climate represents another factor since extremely low or high temperatures, snow fall, usage of snow ploughs, and heavy rain falls may reduce service life of pavement markings (Migletz et al. 1994).

Pavement markings service life expectancy is usually determined based on agency experience, professional judgment, and manufacturer's data. The life expectancy for pavement markings ranges between 6 months to 2 years for non-epoxy paint, between 1 to 5 years for epoxy paint, 2 to 10 years for thermoplastic, 1 to 10 years for cold plastic, and 5 to 10 years for tape (Markow 2007), as Table H-7 shows.

Table H-7. Pavement markings life expectancy.

Component and Material	No. of Responses	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
Lane and Edge Striping	-	-	-	-	-	-
Non-epoxy paint	22	0.5	2	1.1	1	1
Epoxy paint	13	1	5	3.3	4	4
Thermoplastic	16	2	10	4.2	4	5
Cold plastic	8	1	10	4.9	5	6
Polyester	2	2	3	2.3	2.3	-
Tape	5	5	10	6.3	6	5
Thin thermoplastic	1	-	-	1-2	-	-
Preformed thermoplastic	1	-	-	3	-	-
Pavement Markers	-	-	-	-	-	-
Ceramic pavement markers	2	3	3	3	3	3

Table H-7. Pavement markings life expectancy. (Continued)

Component and Material	No. of Responses	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
Raised pavement markers	10	1	5	3.2	3	3
Recessed pavement markers	6	1	5	3.2	2.5	2
Raised snowplowable markers	1	-	-	4	-	-

Source: NCHRP Synthesis 371 – Markow 2007

MnDOT has also guidelines to estimate life expectancy based on traffic volumes as shown in Table H-8.

Table H-8. Expected life of pavement markings in Minnesota.

Material	ADT	
	<1,500	>1,500
Latex Paint	> 1 year	1 year
Epoxy (Plural Component Liquid)	> 5 years	3-5 years
Preformed Polymer Tape or Thermoplastic	> 5 years	> 5 years

Source: MnDOT 2009

The pavement marking model considers that pavement markings in condition D and F require new painting. In case of an age-based analysis, pavement markings with a remaining service life 20 percent below the initial service life require new painting. A pavement marking median service life of 4 years is assumed in the model based on previous studies (Markow 2007) and current data analysis.

H.2.2 Select Performance Models to Forecast the Pavement Marking System Condition

Pavement marking performance models are based on condition or age. Condition-based approach requires periodical condition assessment to develop reliable deterioration models, while the age-based approach estimates the remaining life from historical records. Performance models that can used to forecast pavement markings condition include:

- Exponential functional form
- Weibull distribution

Pavement markings deteriorate due to time, traffic, climate conditions, and the type of materials. NCHRP Report 713 includes discussion of the pavement marking service life, as the replacement decisions are mostly condition-driven. The probability of survival can be calculated as a function of age using the Weibull distribution as shown in Equation H-1 (Ford et al 2012).

$$\gamma_{ig} = \exp(-1.0 \times (g/\alpha)^{\beta})$$

Where γ_{ig} is survival probability as a function of age

g = the age at which the survival probability is sought, in months.

β = shape parameter, 3.87 and the scaling parameter is given by

α = exp (1.1 – 0.58 * Orientation (1 if longitudinal, 0 if transverse) – 0.01 * Initial Retroreflectivity value -0.29 * Road surface type (1 if asphalt, 0 if concrete))

Other deterioration models for pavement markings establish a relationship between retroreflectivity and age. Sarasua et al. (2012) in a study for South Carolina DOT estimated a linear relationship between retroreflectivity and age for yellow solid, yellow skip, and white edgeline markings for waterborne, thermoplastic, and high-build materials. Their model is able to “predict retroreflectivity values within a 20 percent error for approximately 65 percent of the measured pavement marking values for waterborne white edge lines, 90 percent for high-build white edge line markings, 71 percent for waterborne yellow solid” (Sarasua et al. 2012).

A Weibull distribution for the probability of failure of pavement markings based on age can developed from a DOT data inventory. Table H-9 shows a summary of the data statistics used for the development of a Weibull regression model. The statistics results are close to the values previously suggested by Markow (2007).

Table H-9. Pavement marking life expectancy.

Pavement Marking Type	No. of Observations	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
White, Epoxy	62	1	6	3.8	4	6
White, Polyurea	269	1	5	2.9	3	2
White, Thermoplastic	314	1	8	4.5	4	4
Yellow, Epoxy	10	2	4	3	3	2
Yellow, Polyurea	270	1	9	3.5	3	2
Yellow, Thermoplastic	105	1	8	4.6	4	4

Table H-10 shows the Weibull regression model developed in this study using data available from a DOT.

Table H-10. Weibull deterioration model parameters for pavement markings.

Pavement Marking Type	Shape Factor, β	Scaling Factor, α
White, Epoxy	1.838	4.338
White, Polyurea	2.835	3.227
White, Thermoplastic	3.208	5.032
Yellow, Epoxy	2.484	3.492
Yellow, Polyurea	4.301	2.222
Yellow, Thermoplastic	3.151	5.133

Survival probability curves that were developed in this study for the pavement markings are shown in Figure H-2. The curves show the probability that in a certain year pavement markings still comply with the minimum retroreflectivity.

In a simplified approach, linear deterioration over time is modeled based on service life expectancy for different pavement marking types (e.g., white, yellow), and materials (e.g., epoxy, polyuria, thermoplastic). The process to develop a simplified straight-line deterioration model is described in the next section.

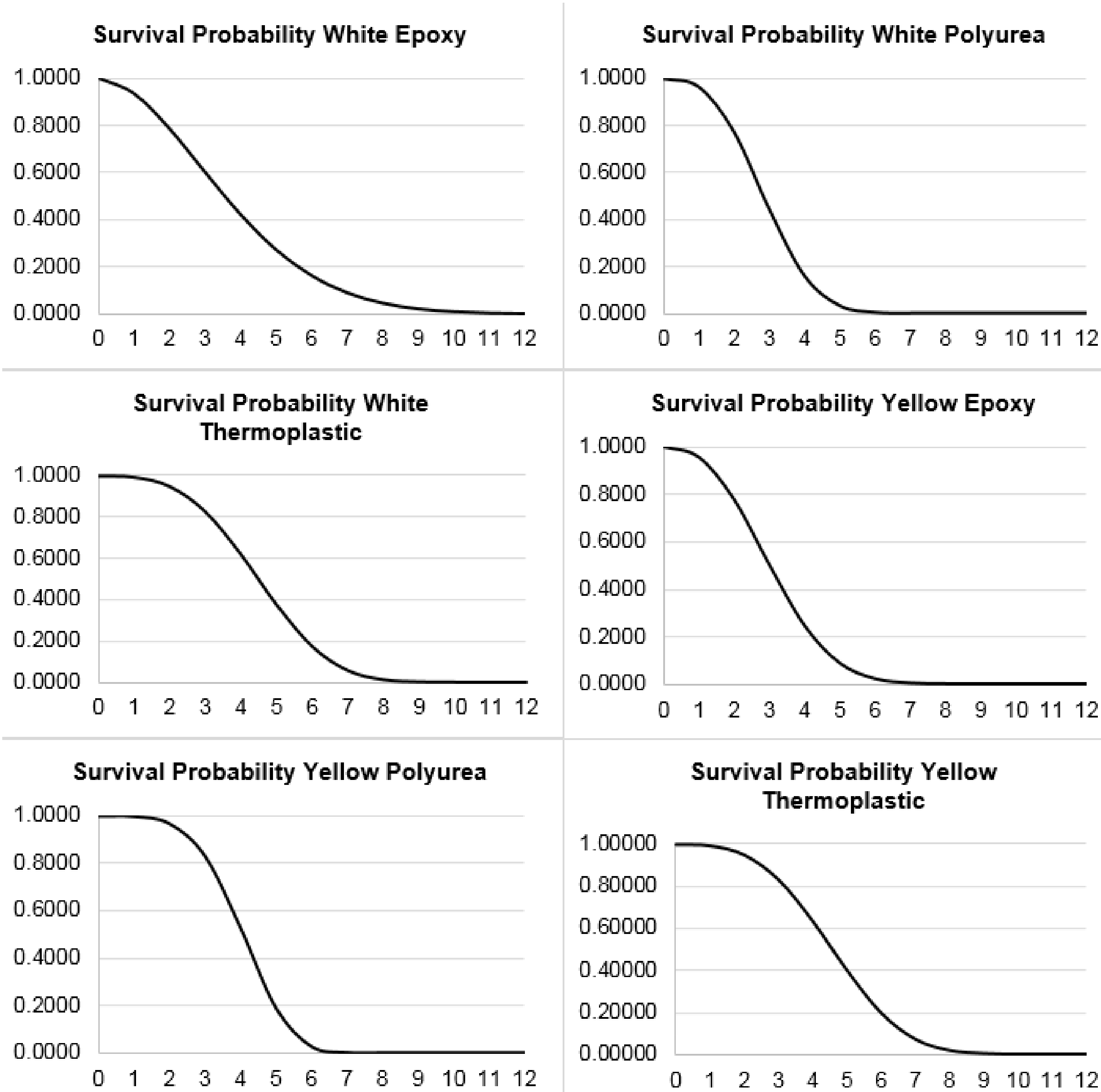


Figure H-2. Failure probability curves for pavement markings.

Development of a straight-line deterioration model from condition data

The performance of the pavement marking system is modeled in the example based on retroflectivity using a straight-line deterioration. The step-by-step process to develop this model is described as follows.

a. Extract data from the pavement marking inventory to analyze deterioration and improvement trends for all the pavement marking sections in the inventory. For the model described in this Appendix, the minimum data include: total length for each pavement marking section, pavement marking color, pavement marking material, and retroreflectivity. This step is done for all the years in the inventory.

b. Deterioration rate is based on minimum retroreflectivity at the beginning of the service life, retroreflectivity at the end of functional service life as shown before in Table H-2 (Bahar et al. 2006), and the mean service life as shown in Table H-6. Straight-line deterioration is assumed to model the condition deterioration for six combinations with two colors (white, yellow), and three pavement marking materials (epoxy, polyuria, thermoplastic).

c. Based on retroreflectivity, the pavement marking system is divided into five condition groups: A, B, C, D, F. Condition A, B, and C complies with the retroreflectivity standards as mandated by FHWA. Condition D indicates that pavement markings will soon not meet the minimum retroreflectivity standard. Condition F means that a pavement marking is below the minimum retroreflectivity threshold. The following equation is used to model the retroflectivity changes along the service life.

$$R_n = R_{n-1} \frac{R_0 - R_{end}}{SL}$$

R_n = lower limit for retroreflectivity that classifies as condition category A (n=1), B (n=2), C (n=3), D (n=4), F (n=5)
R_0 = assumed retroreflectivity at the beginning of service life
R_{end} = minimum required retroreflectivity by FHWA
SL = expected mean service life

d. Each condition category has an associated maintenance activity. If pavement marking groups were in condition A, B, and C no treatment is applied. Pavement marking sections in condition D and F are fully repainted.

H.2.3 Perform the Needs Analysis

The needs analysis identifies maintenance and budget needs to preserve the pavement marking system in an excellent condition, with a high visibility and reflectivity in daytime and nighttime. Maintenance criteria is based on minimum retroreflectivity standards. "Paint" is applied when a pavement marking reaches category D or F to restore the retroreflectivity level. Table H-11 shows the cost estimate for "paint" based on NCDOT data.

Table H-11. Cost of re-painting of pavement markings.

Pavement Marking Type	Cost [$/ft.] [1]
White, Epoxy	0.39
White, Polyurea	0.78
White, Thermoplastic	0.61
Yellow, Epoxy	0.34
Yellow, Polyurea	0.79
Yellow, Thermoplastic	0.61

[1] Cost estimates based on NCDOT data.

If retroreflectivity data are not available, the remaining service life approach is used to determine whether re-painting is necessary. Remaining service life is estimated from current retroreflectivity, initial retroreflectivity (375 mcd/m²/lux) and end-of life retroreflectivity (150 mcd/m²/lux), assuming expected service life of 4 years.

H.3 Step 3: Conduct Delayed Maintenance Scenarios Analyses

H.3.1 Formulate Delayed Maintenance Scenarios

Table H-12 describes the set of scenarios evaluated for pavement markings. 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 performance of pavement marking system and budget needs. Scenarios 3 and 4 are formulated to model delayed maintenance either by policy or by limited budget. Delayed maintenance by policy is modeled by a delayed time cycle, therefore if a pavement marking needs maintenance in year n then this activity is deferred by a 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 division of annual average daily traffic by the length of pavement markings in that particular group.

Table H-12. Key elements to analyze delayed maintenance scenarios for pavement markings.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 5 years	Results
Pavement Marking System Database with Inventory and Condition Assessment	Weibull models for predicting pavement marking retroreflectivity failure Straight line deterioration model 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 a. 80 percent of baseline budget b. 40 percent of baseline budget	Analytical Tool: Spreadsheet based model to forecast pavement marking condition categories over the period of analysis. Reports: • Impact on condition due to delayed maintenance. • Agency costs over time. • Changes in the Pavement Marking System Value and Sustainability Ratio.

Scenario 1 describes the situation of unlimited funding available and all treatments in the preservation plan are applied as needed. The funding needs estimated in scenario 1 become the baseline budget for the other scenarios. Scenario 2 is the opposite and all treatments are deferred while the condition of the pavement marking system 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 80 percent or 40 percent of the annual baseline budget.

In the budget-driven scenario (Scenario 4), pavement marking sections are ranked by a Maintenance Priority Index, which is based on traffic volume, length and location of the pavement marking section. The Dynamic Bubble-Up (DBU) method is used to allocate funds beginning with the pavement marking section with the highest MPI until funds are exhausted (Chang 2007). Highway agencies may use different criteria and/or method to prioritize funding allocation. Pavement marking sections in need of a maintenance or replacement, but delayed due to limited budget, are moved to a lower condition category.

H.3.2 Perform the Delayed Maintenance Scenarios Analyses

Table H-13 details the results of the scenarios described in Table H-12. This table shows the 5-year agency costs, backlog cost in the last year of analysis, as well as the percentage of pavement markings below the minimum retroreflectivity level.

Table H-13. Summary of results for the scenario analyses for the pavement marking system.

Scenario	Description	Total Agency Costs[1]	Backlog Cost[1]	Percent Pavement Marking System below Minimum Retroreflectivity	
				End of Year 5	Critical Year
1	All Needs	$25.22 M	$0	0	2 (Year)
2	Do Nothing	$0	$16.60 M	86	86 (Year 5)
3	Delayed Maintenance a. 1-year cyclical delay b. 3-year cyclical delay	 $15.15 M $14.06 M	 $4.48 M $6.85 M	 22 38	 37 (Year 1) 50 (Year 2)
4	Budget-driven with limited funds a. 80 percent of baseline budget b. 40 percent of baseline budget	 $19.95 M $10.04 M	 $3.62 M $9.95 M	 19 51	 19 (Year 5) 51 (Year 5)

[1]At the end of year 5.

At the beginning of the analysis, the percentage of length of pavement markings below the minimum retroreflectivity is 29 percent. With optimal funding of $25.22 million over a 5-year period, all pavement markings comply with the requirements. This is considered the baseline budget for the other scenarios.

In Scenario 2, where no funding is available over a 5-year period, the backlog costs increase to $16.60 million and 86 percent of the system becomes deficient at the end of year 5.

In Scenario 3.a, when maintenance activities are delayed by 1 year, agency costs are $15.15 million and $4.48 million are backlogged, then 22 percent of the system is deficient at the end of year 5.

In Scenario 3.b, when maintenance activities are delayed by 3 years, agency costs are $14.06 million and $6.85 million are backlogged, then 38 percent of the system is deficient at the end of year 5.

In Scenario 4.a, when maintenance activities are delayed due to limited budget (80 percent of baseline budget), agency costs are $19.95 million and $3.62 million are backlogged, then 19 percent of the system is deficient at the end of year 5. In Scenario 4.b, when maintenance activities are delayed due to limited budget (40 percent of baseline budget), agency costs are $10.04 million, and $9.95 million are backlogged, then 51 percent of the system is deficient at the end of year 5.

H.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 Pavement Marking System Condition and Service Life

At the beginning of the analysis, 34 percent of pavement marking system is in condition A, 19 percent in condition B, 11 percent in condition C, 7 percent in condition D, and 29 percent in condition F, as Figure H-3 shows.

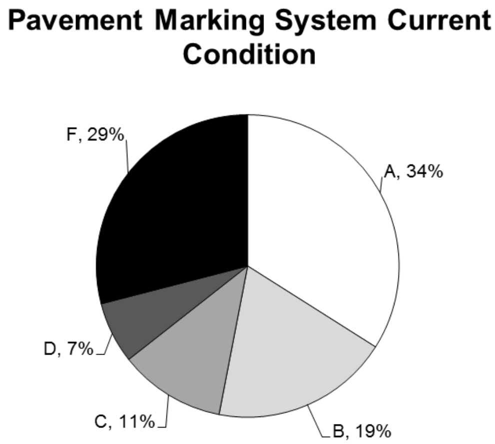


Figure H-3. Pavement marking system current condition.

Figure H-4 shows the pavement marking condition categories at the end of year 5. In Scenario 1 (All Needs), there are no assets in condition F, while for the delayed maintenance scenarios this condition group increases to 22 percent and 38 percent for 1 and 3-year delay respectively. In Scenario 2 (Do Nothing), 86 percent of the markings fall into the F category. In Scenario 3.a (Delayed maintenance by 1 year), majority of the pavement markings are in condition D (35 percent) and F (22 percent), while A decreases to 14 percent from initial 34 percent in year 0. In Scenario 3.b (Delayed maintenance by 3 years), 38 percent of pavement markings ends up in condition F, only 4 percent in condition D, and 16 percent in condition A.

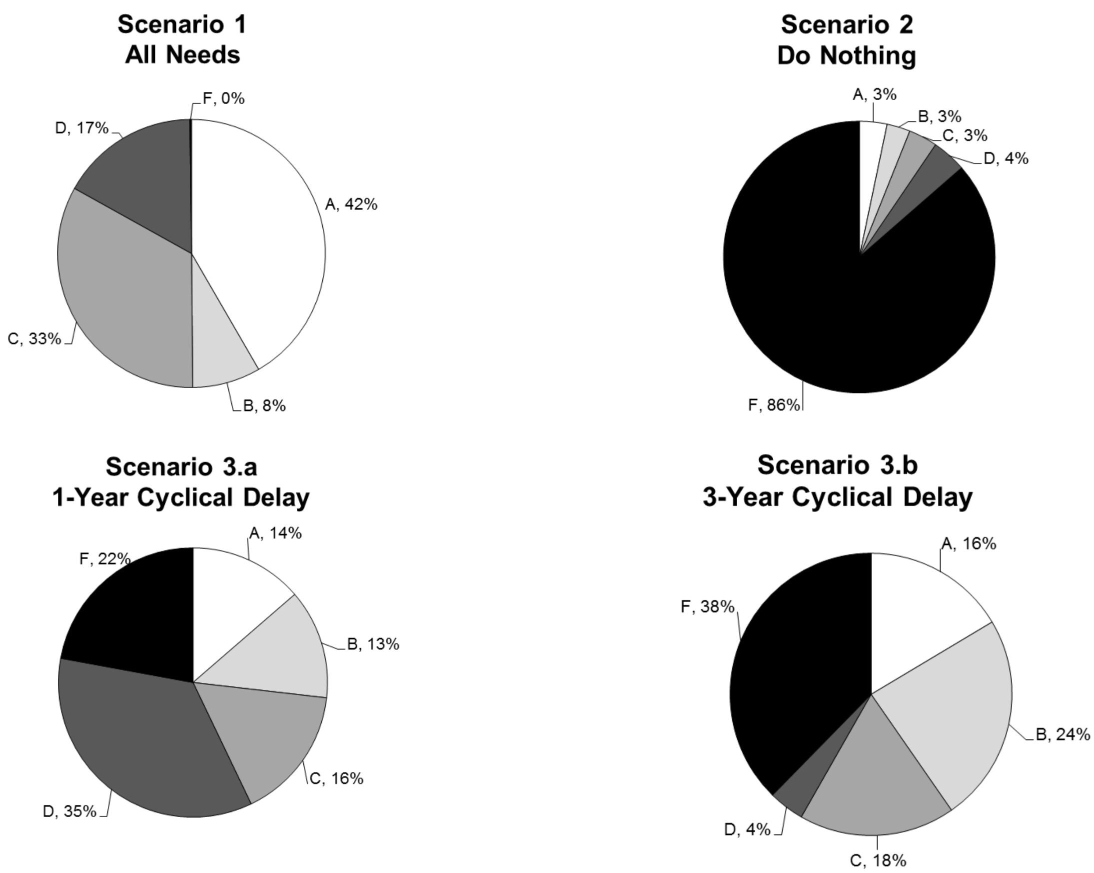


Figure H-4. Pavement marking system condition categories at the end of analysis period, year 5.

Figure H-5 shows the changes in condition categories over time under different scenarios. In Scenario 1, where all needs are funded, by the last year of analysis 42 percent of pavement markings are in condition A and none in condition F. In Scenario 2, where no funding is allocated during the analysis period, by year 2 more than half of the system is in condition F and by the fifth year 86 percent are in condition F. In Scenario 3.a, where all maintenance is delayed by 1 year, and Scenario 3.b, where all maintenance is delayed by 3 years, the maintenance deferral results in a decrease in pavement marking assets in condition A while condition F increases to 38 percent in Scenario 3.b and decreases to 29 percent in Scenario 3.a.

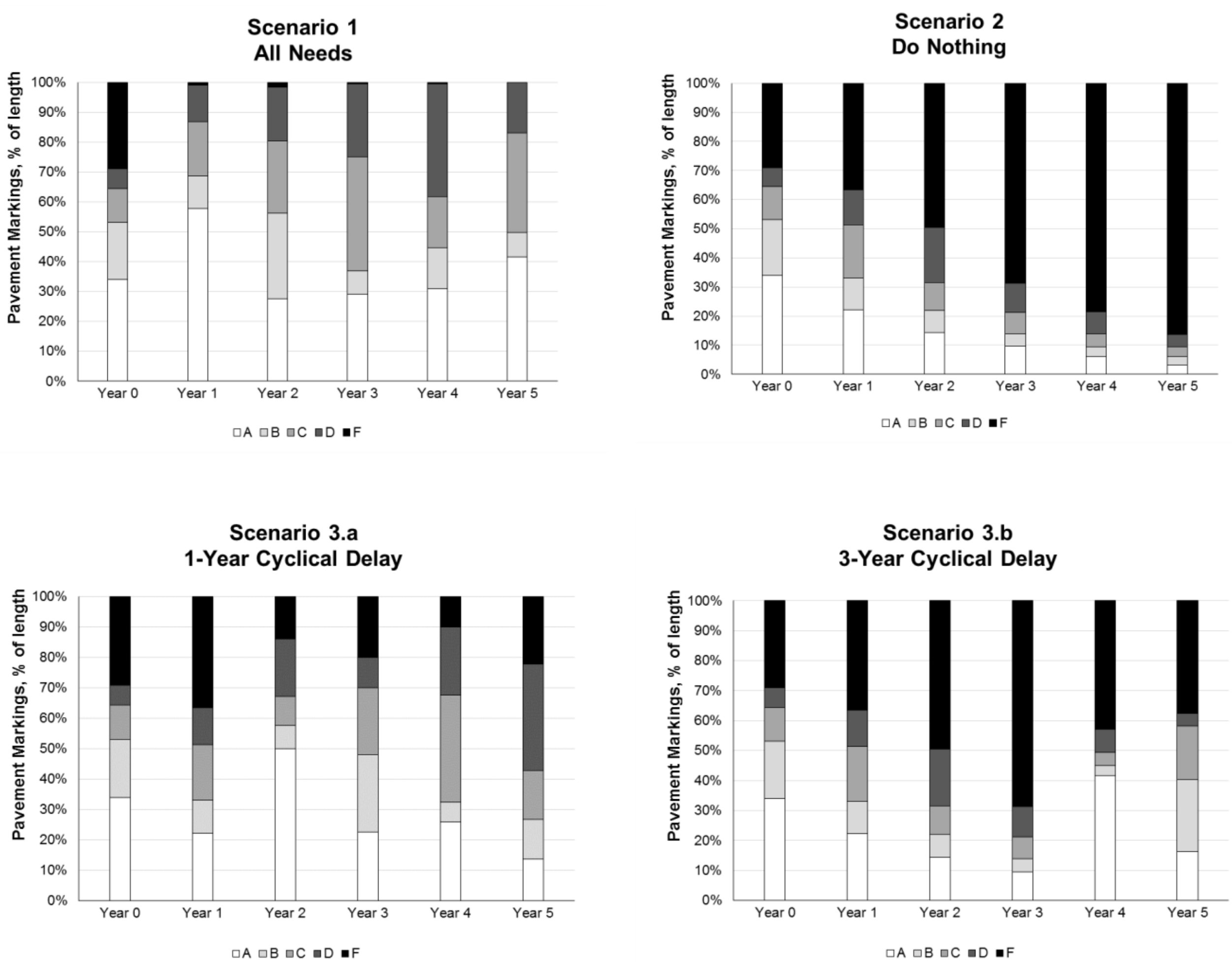


Figure H-5. Pavement marking condition categories over time, 5 years.

Figure H-6 shows the changes in remaining service life under different scenarios. The remaining life distribution is correlated with the condition as shown in Figure H-4. Pavement markings belong to the remaining life category RL1 when they are between 100-80 percent of their expected service life (that is, between 4 to 3.2 years of remaining life). Category RL2 means remaining life between 3.2 and 2.4 years (80 percent - 60 percent of expected remaining life). Category RL3 means remaining life between 2.4 and 1.6 years (60 percent - 40 percent of expected remaining life). Category RL4 means remaining life between 1.6 and 0.8 years (40 percent -

20 percent of expected remaining life). Finally, category RL5 is for pavement markings with less than 20 percent of their service life.

Figure H-7 shows that when no funding is allocated, then by year 2, 50 percent of pavement markings are in condition F, below the FHWA requirements. Scenario 3.a results in 22 percent of pavement markings below minimum retroreflectivity at the end of five years. Scenario 3.b follows a similar trend as Scenario 2 in the first 3-year deferral period reaching 69 percent of pavement markings below minimum retroreflectivity (condition category F), then the percentage goes down to 38 percent.

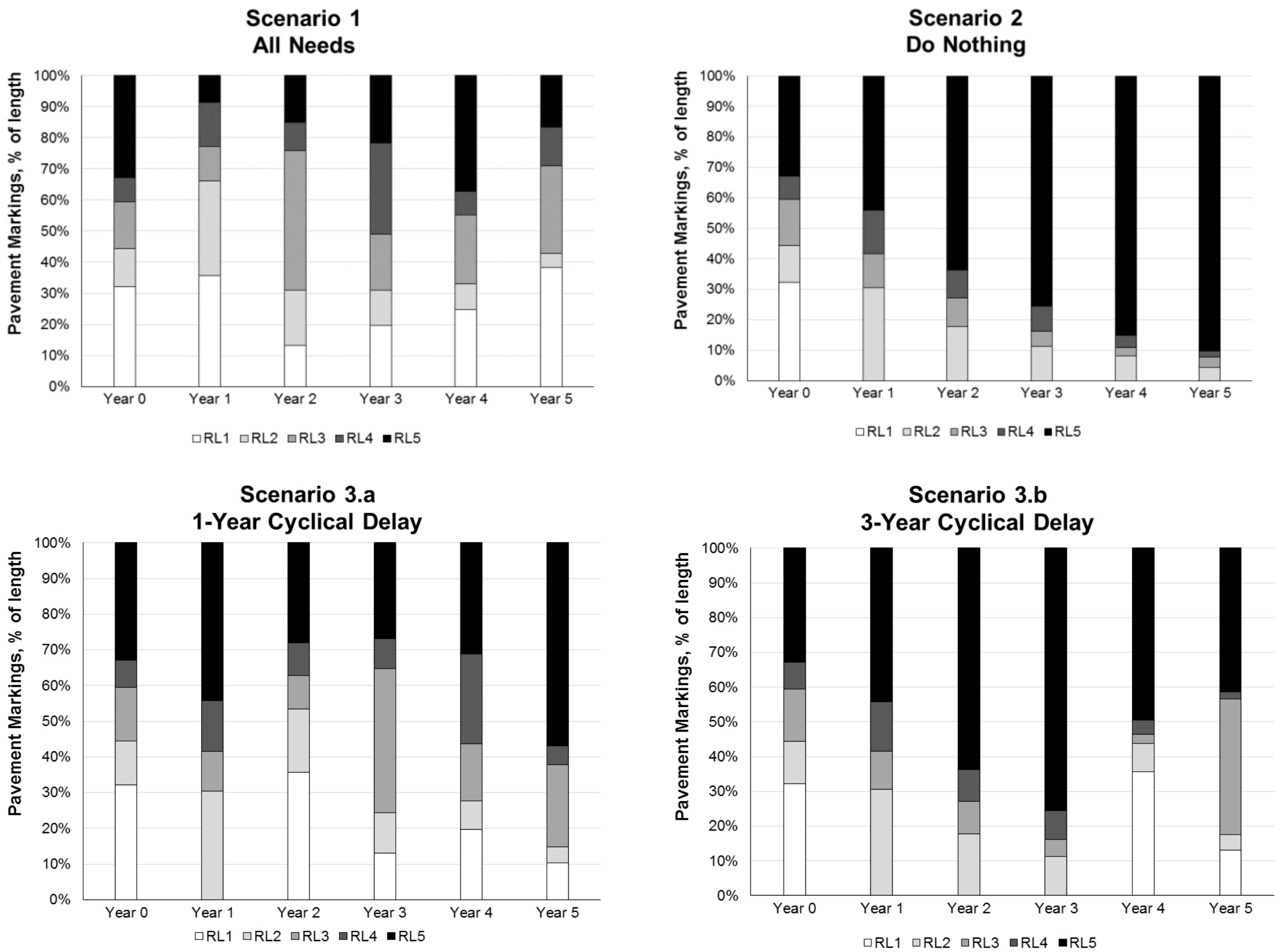
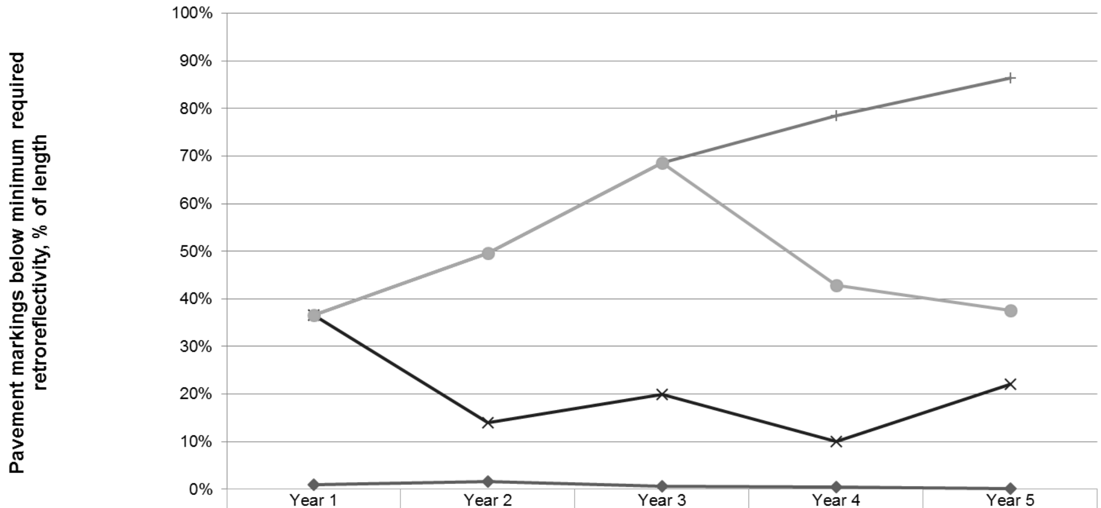


Figure H-6. Pavement marking system remaining service life over time, 5 years.



	Year 1	Year 2	Year 3	Year 4	Year 5
Scenario 1 - All Needs	1%	2%	1%	0%	0%
Scenario 2 - Do Nothing	37%	50%	69%	78%	86%
Scenario 3.a - 1-Year Cyclical Delay	37%	14%	20%	10%	22%
Scenario 3.b - 3-Year Cyclical Delay	37%	50%	69%	43%	38%

Figure H-7. Percentage of pavement markings below minimum retroreflectivity level.

Consequences on Future Budget Needs

If maintenance activities are delayed, not only pavement marking system condition deteriorates and system value goes down, but also unfunded backlog accumulates. Figure H-8 shows the unfunded backlog which is $0 for Scenario 1 (All Needs), and increases up to $16.6 million for Scenario 2 (Do Nothing). The backlog for Scenario 3.a ranges between $6.8 million and $2.1 million, while for Scenario 3.b the backlog range is up to $13.1 million.

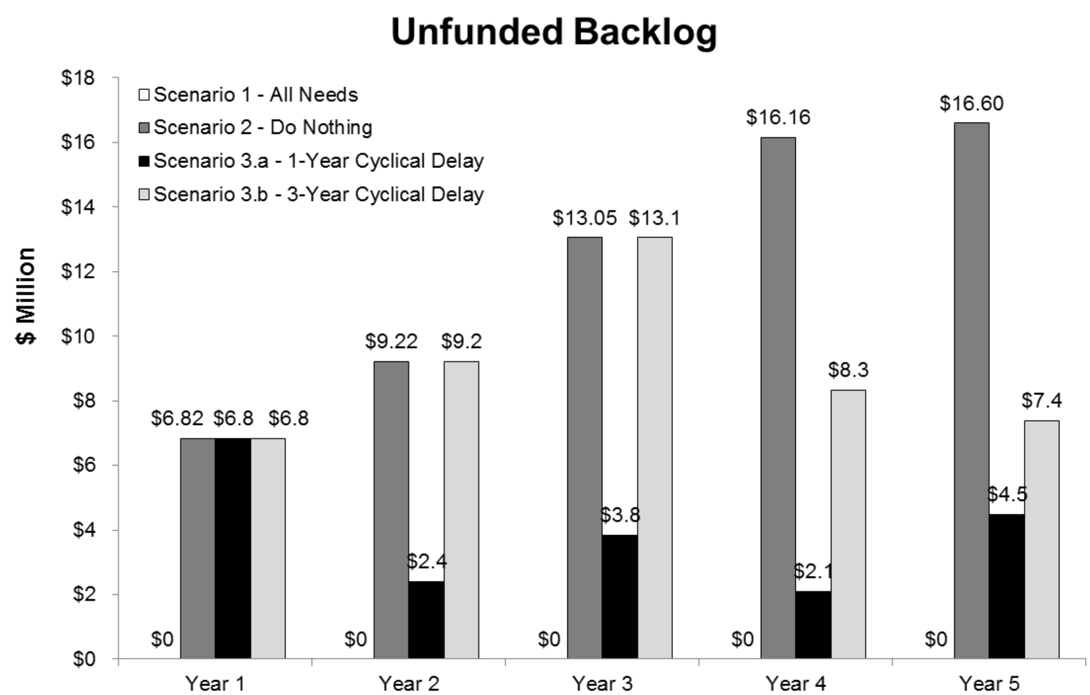
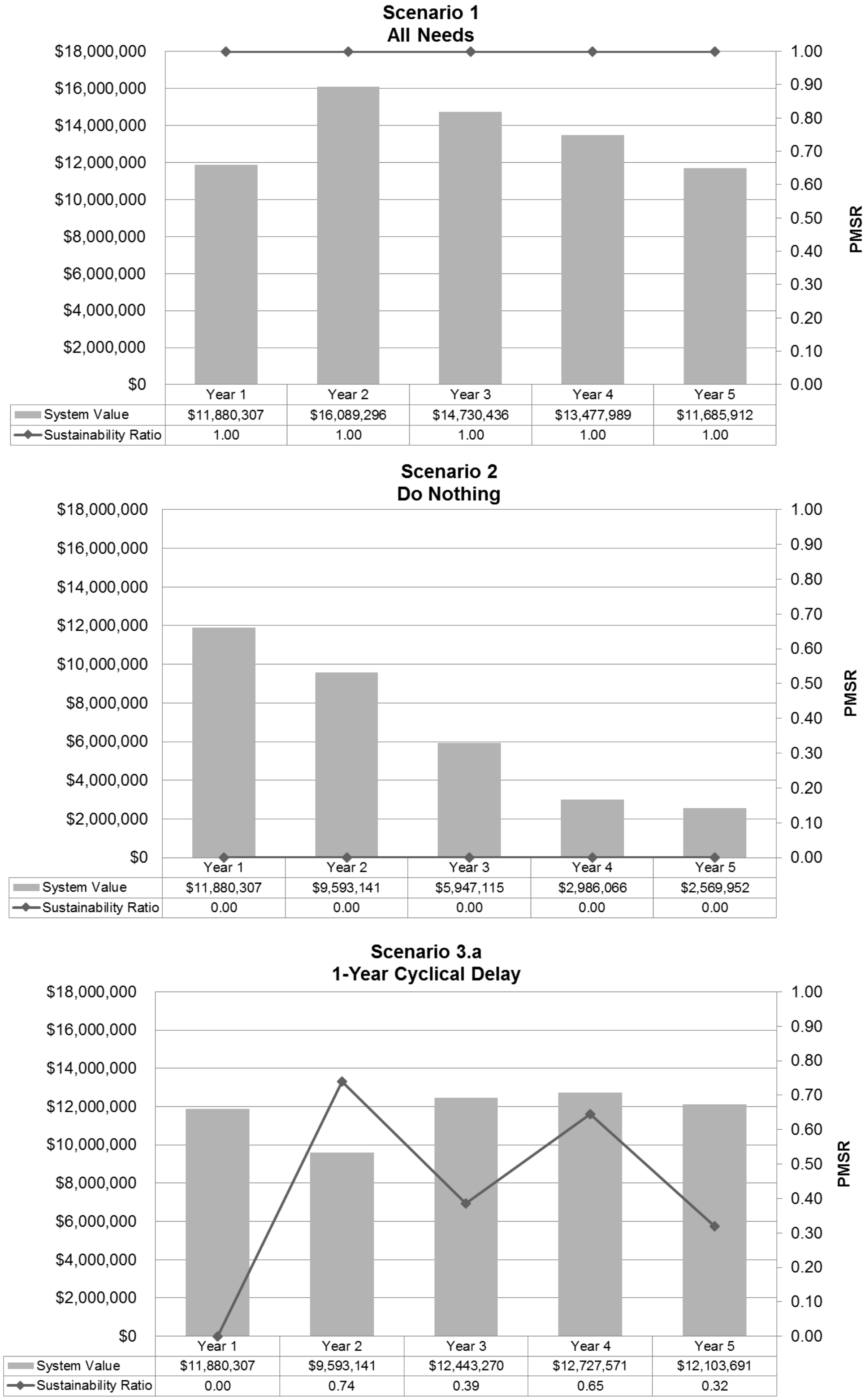


Figure H-8. Comparison of unfunded backlog costs over the analysis period.

Consequences on the Pavement Marking System Value

Figure H-9 shows the pavement marking system value together with the pavement marking sustainability ratio (PMSR) over the analysis period of 5 years. PMSR indicates on a scale 0 to 1 the percentage of budget needs that are allocated each year. In Scenario 1, all needs, the system value ranges between $11.7 and $16.1 million. In Scenario 2, where treatments are performed during the analysis period, the system value goes down to $2.6 million. In Scenario 3.a, where maintenance activities are delayed by 1 year, the system value recovers after the drop in year 2 and stays around $12 million. In Scenario 3.b, where maintenance is delayed by 3 years, the system value starts to recover in year 5 but only to $9 million.



Scenario 1: All Needs

	Year 1	Year 2	Year 3	Year 4	Year 5
System Value	$11,880,307	$16,089,296	$14,730,436	$13,477,989	$11,685,912
Sustainability Ratio	1.00	1.00	1.00	1.00	1.00

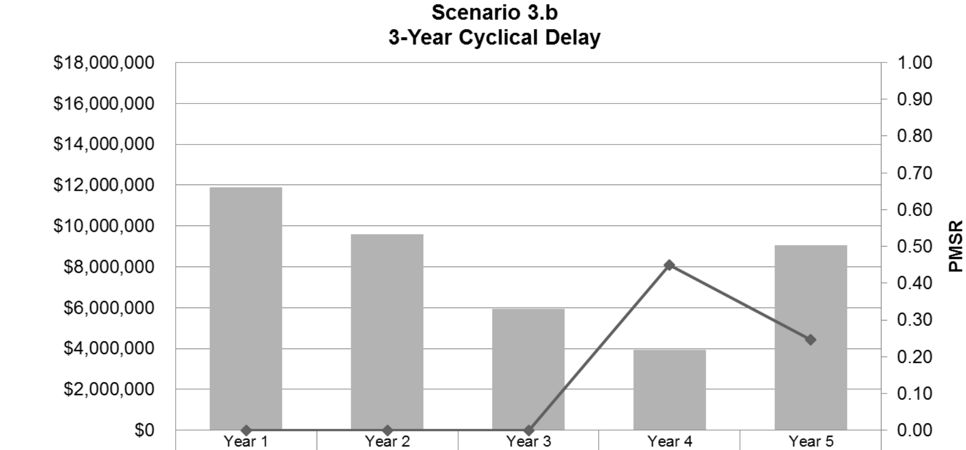
Scenario 2: Do Nothing

	Year 1	Year 2	Year 3	Year 4	Year 5
System Value	$11,880,307	$9,593,141	$5,947,115	$2,986,066	$2,569,952
Sustainability Ratio	0.00	0.00	0.00	0.00	0.00

Scenario 3.a: 1-Year Cyclical Delay

	Year 1	Year 2	Year 3	Year 4	Year 5
System Value	$11,880,307	$9,593,141	$12,443,270	$12,727,571	$12,103,691
Sustainability Ratio	0.00	0.74	0.39	0.65	0.32

Figure H-9. Pavement marking system value and sustainability ratio over the analysis period.



	Year 1	Year 2	Year 3	Year 4	Year 5
System Value	$11,880,307	$9,593,141	$5,947,115	$3,944,251	$9,066,107
Sustainability Ratio	0.00	0.00	0.00	0.45	0.25

Figure H-9. Pavement marking system value and sustainability ratio over the analysis period. (Continued)

H.4 Summary

The scenario results that were summarized in Table H-13 demonstrate the effects of delaying maintenance to pavement markings. Delaying maintenance activities results in increased number of pavement markings in condition category F. Specific results for this case study include the following:

- In Scenario 1, all needs, repainting of pavement markings once they have reached their service life results in an allocated budget of $25.22 million or total agency costs, a pavement marking system in good condition (42 percent in condition category A), no backlog costs, and a system value of $11.7 million.
- Scenario 2, do nothing, results in $16.6 million backlog costs, a pavement marking system poor condition (86 percent in condition category F), and the system value decreases by $9.1 million.
- Scenario 3.a, 1-year deferral period, reduces the agency costs by approximately $10 million, and there is an increase of approximately $4.5 million in the unfunded backlog as a result of delayed maintenance.
- Scenario 3.b, 3-year deferral period, reduces the agency costs by approximately $16 million. There is an increase of approximately $7.4 million in unfunded backlog as a result of delayed maintenance. Also the system value decreases by $2.6 million, as almost 38 percent of the pavement system is below required retroreflectivity levels.
- Scenario 4.a, budget-driven with 80 percent of baseline budget, reduces the agency costs by approximately $5.3 million. Unfunded backlog increases by approximately $3.6 million due to delayed maintenance, and 19 percent of the pavement marking system is below required retroreflectivity levels.
- Scenario 4.b, budget-driven with 40 percent of baseline budget, reduces the agency costs by approximately $15.2 million. Unfunded backlog increases by $10 million due to delayed maintenance, and 51 percent of the pavement marking system is below required retroreflectivity levels.

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