APPENDIX F

Procedure to Quantify Consequences of Delayed Maintenance of Guardrails

The purpose of guardrail systems is to decrease the severity of potential accidents caused by errant vehicles leaving the roadway and to provide a barrier between the vehicle and potential hazardous areas (FHWA 2008). Multiple guardrail systems have been developed and tested to meet the current performance standard provided by NCHRP 350 and the most current "Manual for Assessing Safety Hardware" (MASH) standards. "Guardrail" is the term widely used when referring to longitudinal barriers installed along the roadside or along a roadway median. Guardrails systems can be considered a roadside hazard therefore proper design and proper placement greatly affects the intended performance; redirect vehicles or assist vehicles to come to a complete stop (NCHRP 2009). There are many guardrail systems such as cable barriers, bull nose rail system and concrete barriers and many W-beam guardrail system configurations that are currently in use. The strong post W-beam guardrail system consists of a W-beam rail element, strong posts (wood or steel), and "block outs" (wood or steel) to provide space between the posts and the beam (FHWA 2008). The strong post W-beam guardrail is the most widely used guardrail system configuration in use in the United States. Delaying maintenance and necessary replacement activities of the guardrail system affects the systems overall condition which directly impacts the agencies future maintenance and replacement costs. Figure F-1 shows the procedure to quantify the consequences of delayed maintenance of guardrail systems.

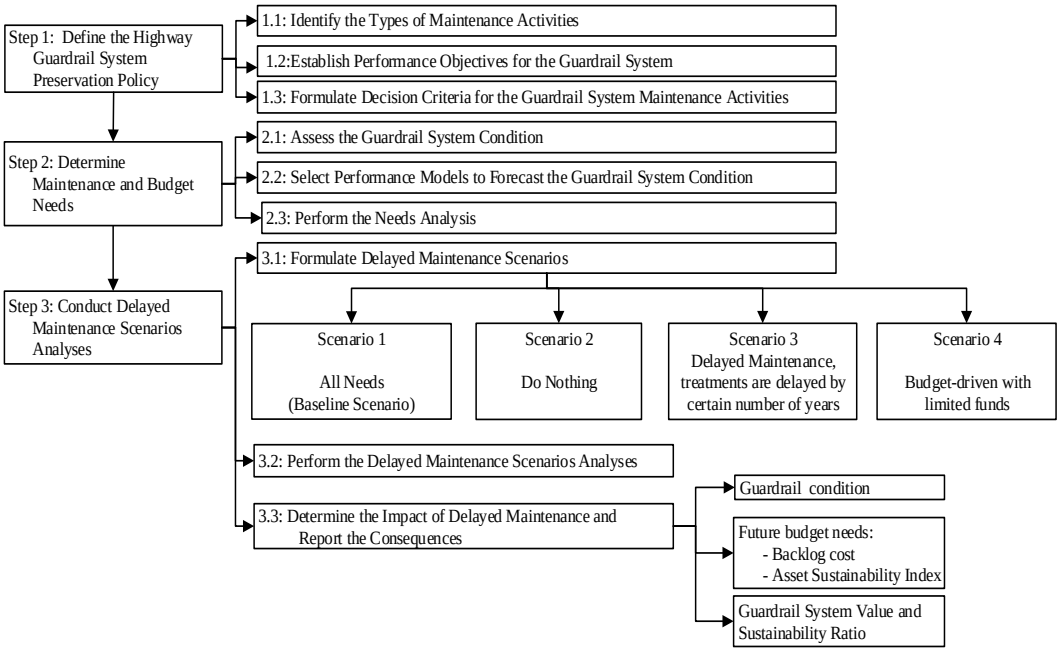


Figure F-1. Procedure to quantify the consequences of delayed maintenance of guardrail systems.

As the maintenance activities are delayed the guardrail system condition continues to deteriorate. The deterioration of the guardrail system condition results in a higher maintenance costs due to the increase of the guardrail system requiring maintenance. Delaying maintenance activities will not only impact future maintenance costs but will also increase the likelihood of a fatal car accidents resulting from a deteriorated guardrail system.

F.1 Step 1: Define the Guardrail System Preservation Policy

The preservation policy for the guardrail system is usually formulated by a central office that provides general recommendations for maintenance, specifications for materials, and criteria to prioritize funding allocation. The following sections in step 1 discuss guardrail system preservation policies, target performance objectives, and decision criteria for performing maintenance activities.

F.1.1 Identify the Types of Maintenance Activities

The DOTs use varying routine or corrective maintenance procedures based on the available funding, staff, and equipment. Guardrail condition deteriorates over time, as all highway assets do, but maintenance or replacement is usually performed when guardrails receive an impact that results in physical damage. Guardrails are highly associated with public safety therefore repairs are normally performed immediately after an incident report or notification is received. Depending on the damage and resources, various maintenance activities can be applied to the guardrail system. W-beam guardrail systems are the most widely used in the United States, and maintenance activities for this type of guardrail are as follows.

Preventive and Routine Maintenance:

Preventive maintenance usually only includes the following activities:

- Washing
- Tightening of fittings (e.g. screws and bolts)

Routine maintenance is minimal and includes the following activities (MnDOT 2010):

- Replace post attachment bolts
- Realign posts damaged by snowplowing
- Apply herbicides along roadside barriers to avoid difficulties involved in mowing grass and weeds along and under the barrier
- Remove dirt build-up, debris, and soil along the guardrail system
- Remove litter that might interfere with the performance of the guardrail system

Crash Related Maintenance:

Depending on the damage and resources, various maintenance combinations are applied to the guardrail system. The following are general guidelines for W-beam guardrail system routine maintenance and crash (replacement) related preservation activities: (MnDOT 2010)

1. All guardrail parts must meet appropriate specifications. If used or salvaged parts are used, they must be in good condition.
2. Modifications to the barrier must not be made unless consistent with more modern standards for that barrier type. Barrier components or features must not be omitted.
3. During repairs, roadside conditions affecting performance should be checked, such as introduction of new fixed objects.
4. If significant damage occurs to a substandard barrier or terminal, it should be upgraded to current standards.
5. Feedback on recurring problems should be provided to design and construction staff so future installations can be improved.

F.1.2 Establish Performance Objectives for the Guardrail System

This step involves determining what maintenance activities should be included in the guardrail system preservation program. The criteria for maintenance activities depend on the preservation policy and the performance measures selected by the agency. NCHRP 470 mentions that performance measures are quantifiable measures "of performance to determine progress toward specific, defined organization objectives based on statistical number evidence." Sample measures include the percent of damage of a guardrail system, and the percent of guardrail systems below standard. Level of service (LOS) and numerical ratings are "expressed as a tangible, measurable goal against which achievement can be compared" (NCHRP 2015).

Most of the maintenance activities are formulated based on field surveys to evaluate if the guardrails are still in functional conditions. For example, CDOT mentioned that two condition indicators for guardrails include percent of guardrails in the system not meeting specifications and percent guardrails damaged or deteriorated. Condition indicator ratings range from 4 to 0, which corresponds to 0 percent of guardrails are functional and 15 percent or greater of guardrails are not functional. These ratings are then used to compute a letter grade, A to F, for maintenance Level of Service (MLOS) for guardrail assets. MLOS is then used for budgeting purposes to establish a base line for current asset condition and to forecast the guardrail system performance. Utah DOT uses the LOS approach and conducts semiannual checks to gather the following information:

- Length in feet of guardrail that needs to be replaced or repaired due to damaged panels, missing hardware, or leaning, bent, or broken posts.
- Report sections where the guardrail is sagging.

Utah Department of Transportation (UDOT) uses a grade scaled based on the percentage of deficient features as shown in Table F-1. The percentage of deficient guardrail length to total guardrail length is calculated to determine the grade. If the guardrail system has 0-10.02 percent deficient length, then the guardrail system falls into the "A" grade range with 90-100 percent of features in acceptable conditions. If the guardrail system has 10.03-20.01 percent deficient length, then the guardrail system falls into the "B" grade range with 80-90 percent of features in acceptable conditions. The other grades are broken into percent deficient ranges as previously described. The guardrail system grading scale approach is adopted in an example to illustrate the consequences of delaying maintenance of guardrail systems.

Table F-1. Guardrail system grading scale.

Percent Deficient	Grade	Percent Deficient	Grade
0.00-3.43	A+	26.82-30.00	C-
3.44-6.83	A	30.01-33.40	D+
6.84-10.02	A-	33.41-36.79	D
10.03-13.42	B+	36.80-39.99	D-
13.43-16.82	B	40.00-43.39	F+
16.83-20.01	B-	43.40-46.78	F
20.02-23.41	C+	46.76-30.00	F-
23.42-26.81	C		

Source: UDOT, 2012

The grading scale, is also used as a target scale by UDOT's Quality Improvement Team (QIT) for maintenance MMQA in 2013. The QIT consists of Region Directors, District Engineers, Area Supervisors and Station Foremen.

At the statewide level, the MMQA+ is used (UDOT 2012):

- To communicate how well UDOT is preserving their infrastructure.

- As a budgeting tool.
- To determine where more resources could be valuable or where resources can be reduced.
- To help establish goals for future levels of maintenance with consideration of available budget and resources. At the station level, the MMQA+ is used (UDOT 2012):
- To prioritize and schedule work activities. Station personnel review MMQA+ reports and determine which activities in their station should receive priority given their current conditions, established targets, and available budgets.
- To compare budgets to current asset condition and request that funding be moved from one activity to another to best meet MMQA+ targets.

F.1.3 Formulate Decision Criteria for Guardrail Maintenance Activities

This step will focus on determining maintenance activities for the guardrail system. The decisions criteria should specify required maintenance activities based on reaching the preferred LOS. After inspections are complete, it would be determined if interventions are necessary. The decision criteria should specify what maintenance activities are needed based on reaching the guardrail requirements. Guardrail maintenance repairs are identified after conducting field inspections. Agencies typically conduct "periodic review, inspection and maintenance of in-service traffic barriers" to ensure that the guardrail systems functions as in intended to (MnDOT 2010).

Agencies have varying needs, at the least, an annual visual inspection is recommended on a sample of guardrails. Inspections also occur following a crash report or complaint. UDOT conducts semiannual inspections that include reporting deficient length, missing components, and the total length of the guardrail system (UDOT 2012). Other DOTs have different practices, South Carolina DOT (SCDOT) inspects guardrail systems located on the Interstate system every three years, or immediately after a major damage notification is received by the agency while guardrail systems located on non-interstate routes are inspected every five years (SCDOT 2010).

The guardrail maintenance inspections should assess the condition of guardrail, concrete barrier, and cable barrier on state routes. Desired condition for panels should be undamaged, and all posts, offset block, panels and connection hardware be in place. Deficient condition of panels happens when panels are damaged and posts may be leaning, bent, or broken. Moreover, offset blocks, panels and connection hardware may be missing and guardrail sections or cable runs may be sagging. Deficiency is reported in length in feet of guardrail or barrier that needs to be replaced or repaired due to damaged panels, missing hardware, or leaning, bent, or broken posts. Deficient measurements should include the length of the pieces that need to be replaced, though only a portion may be deficient. Guardrail systems that do not conform to the current standards are also documented, and if they are still in good condition their upgrade may be delayed until a full-reconstruction project is scheduled. An example of an inspection report is shown in Figure F-2.

Maintenance activities for guardrails are tied to a level of service system to formulate the decision criteria. The LOS of a guardrail is described in terms of four damage condition states:

- "Minor: Damage to the guardrail system is minor. Although the guardrail system may not be aesthetically pleasing, it will perform its intended function.
- Moderate: Damage to the guardrail system is obvious but the guardrail system still maintains its structural integrity and will work for most traffic conditions.
- Severe: Damage to the guardrail system is so severe that the guardrail system no longer functions as designed or has become a hazard itself to the traveling public." (SCDOT 2010)

The W-Beam Guardrail Repair Guide (FHWA 2008) mentions that replacements of guardrails occur during the following situations:

- Any existing guardrails that do not comply with the current Department of Transportation or AASHTO MASH guidelines.

- When the guardrail terminal is damaged, it should be investigated to determine whether the guardrail terminal needs to be repaired, replaced, or eliminated.

Guardrail Inspection Form

General Information					
Date of Inspection	District	County	Road Type	Route Number	Aux

Guardrail Segment Information		Guardrail Condition	
Guardrail Identification Number		Measured Height to Top of Rail (Inches)	
Guardrail ID Tag Condition		Number of Rotten Posts	
Guardrail Segment Length (feet)		Highest Number of Consecutive Rotten Posts	
Direction of Travel (N,S,E,W)		Number of Posts with Missing or Loose Hardware	
End Terminal	Type: _____ Quantity: _____	Highest Number of Consecutive Posts with Missing or Loose Hardware	
Shoulder Condition	☐ Good ☐ Poor	Guardrail Damaged? ☐ Yes ☐ No	

Damaged Guardrail Information			
Type of Damage: ☐ Severe ☐ Moderate ☐ Minor			
Length of Damage (feet):		End Terminal Damaged? ☐ Yes ☐ No	
Measured Horizontal Misalignment (inches):		Number of Damaged Terminals:	
Number of Damaged Posts:		Highest Number of Consecutively Damaged Posts:	

Notes or Comments:

Inspected By: _____ (Name) _____ (Signature)

Source: SCDOT, 2010

Figure F-2. Example of a guardrail inspection form.

F.2 Step 2: Determine Maintenance and Budget Needs for the Guardrail System

F.2.1 Assess the Guardrail System Condition

There are a few DOTs that have a management system with condition data and cost for maintenance work. In most of the cases, there is a lack of maintenance records and condition data for these assets. DOTs perform annual visual inspection for height requirements, lateral offset, and completeness of installation, but hard copies of the inspection forms are kept at maintenance yards. Some maintenance yards may be keeping a manual tracking system for their inspection forms. Inspections do not measure asset performance, and only indicate

whether or not the guardrail condition passes the performance criteria specified in the DOT guideline and specifications.

Utah DOT is one of the few state agencies that uses an Operations Management System (OMS) to track condition data and guardrail maintenance costs. UDOT conducts semiannual inspections to identify the percent of assets that are deficient within a station (section of highway). Based on this percentage, the station is given a Level of Maintenance (LOM) grade which is expressed with a letter (i.e., A, B, C, D, and F). There is no statewide performance target, but there is a target grade (A to C) 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).

F.2.2 Select Performance Models to Forecast the Guardrail System Condition

Guardrail assets are maintained based on condition. For example, UDOT has regression curves based on performance versus the annual cost to maintain the asset. These regression curves are used to formulate the budget needed to improve or maintain the guardrail system performance. UDOT is also at the starting stages in considering an evaluation of the safety benefits of guardrail, pavement marking, and sign assets (UDOT 2012).

In order to quantify deterioration, UDOT uses the deterioration rates given in Table F-2. It is assumed that if there are crashes or accidents and not repairs, the condition of guardrail gets worse by one stage. The interval to move from one condition category into another may change depending on the guardrail material. W-Beam guardrails may last 10 to 20 years if there are no vehicle crash accidents. Other types of guardrails have longer lives (e.g. galvanized guardrail and concrete barriers) and may last thirty years or more if not physically damaged. However, in practice, deterioration rates should not only consider material aging but also crashes that, without proper maintenance and repairs, affects the entire guardrail system. Therefore, the ten-year period to move from condition A to F as shown in Table F-2 should be adjusted to local conditions and maintenance practices.

Table F-2. Example of guardrail system deterioration condition rate.

Deterioration in Condition Rating	Time After Installation (Years)
From A to B	2.5
From B to C	2.5
From C to D	2.5
From D to F	2.5

Note: UDOT recommended analysis period.

Deterioration and improvement matrices from condition data

The performance of the highway guardrail system is modeled by transition matrices to simulate deterioration or improvement in the guardrail condition. Condition categories (A, B, C, D, and F) are based on the percentage of deficient guardrail lengths in a section of highway. The parameters for the transition matrices are obtained from statistical analysis using historical data. The step-by-step process to develop the transition matrices is as follows:

a. Extract data from the guardrail inventory to analyze deterioration and improvement trends for all the guardrail sections in the inventory. As a reference, the Asset Management Data Collection Guide, Task Force 45 Report (AASHTO 2006), provides guidelines about guardrails data for the inventory. For the model described in this Appendix, the minimum data include: total length for each guardrail section, and defective guardrail length. This step is done for all the years in the inventory.

b. For two consecutive years (year n and n+1), compare the condition category for each guardrail section using the station and name of the guardrail or ID number, and split the sections in two groups: deteriorated and improved sections. Guardrail sections with a higher defective percentage in year n+1 were compared to year n for the condition deterioration transition matrix, and guardrail sections with a lower defective percentage in year n+1 were compared to year n for the improvement condition transition matrix.

c. Transition matrices are defined by the number of sections that moves from one condition to another and by the increase or decrease of the deficient guardrail length 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 guardrail sections in the model.

In the deterioration transition matrix, the percent of deficient guardrail length increases in the following year as shown in Table F-3. For example, if a group of guardrails at year n is in condition A, then there is a 67 percent probability that the next year the condition will remain A, 18 percent probability that more guardrails will become deficient and place the group in condition B, 8 percent probability that the condition will become C, 0 percent probability that the condition will become D, and 7 percent probability that the condition will become F.

Table F-3. Guardrail deterioration transition matrix.

% from / to	A	B	C	D	F
A	67%	18%	8%	0%	7%
B		43%	43%	14%	0%
C			35%	40%	25%
D				45%	55%
F					100%

In the deterioration model, for guardrails in condition A at year n and stay in this category, the increase in deficient guardrail length is 1.7 percent. For guardrails that are condition A and move to condition B the next year, the increase in deficient guardrail length is 8.7 percent. For guardrails that are in condition A and move to condition C the next year, the increase in deficient guardrail length is 20.0 percent. For guardrails that are in condition A and move to condition D, the increase in deficient guardrail length is 35.2 percent. For guardrails that are in condition A and move to condition F in the next year, the increase in guardrails is 50.3 percent.

Table F-4. Increase of deficient guardrails in the deterioration matrix.

from / to	A	B	C	D	F
A	+1.7%	+8.7%	+20.0%	+35.2%	+50.3%
B		+4.0%	+8.8%	+23.9%	+38.9%
C			+2.5%	+12.6%	+22.8%
D				+19.9%	+43.1%
F					+5.8%

d. For the improvement transition matrix, the number of guardrail sections that improve from year n to year n +1 is determined. The number of sections in category F in year n that remains in category F in year n+1, sections 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 sections for each condition transition group was used for the general model. In the case that there are more than two years, the probability, improvement and deterioration amount within whole study years going to be counted as the base years to calculated the transition matrix.

In the improvement transition matrix, the percent of deficient guardrails decreases in the following year due to maintenance activities as shown in Tables F-5 and F-6. For example, in the improvement model if the guardrail group is in condition B and maintenance treatments are applied to treat the deficient guardrails, then the next year there is a 67 percent probability that the condition will become A and 33 percent probability that despite the improvement the guardrail will still classify as B.

Table F-5. Guardrail improvement transition model.

% from / to	A	B	C	D	F
A	100%				
B	67%	33%			
C	50%	15%	35%		
D	100%	0%	0%	0%	
F	100%	0%	0%	0%	0%

In the improvement model, guardrails that are in condition B and move to condition at the next year, the decrease in deficient guardrail is 8.9 percent. For guardrails that in condition B and stay in this condition, the decrease in deficient guardrail length is 1.1 percent.

Table F-6. Decrease of deficient guardrails in the improvement model.

from / to	A	B	C	D	F
A	-1.6%				
B	-8.9%	-1.1%			
C	-18.1%	-14.6%	-3.3%		
D	-4.6%	-5.9%	-7.2%	-8.5%	
F	-10.0%	-11.3%	-12.6%	-13.9%	-15.2%

F.2.3 Perform the Needs Analysis

The needs analysis determines the maintenance activities and budget required to preserve the guardrail system in acceptable conditions. The model identifies the needs of maintenance and replacement of deficient guardrails, and forecast the guardrail condition for the highway system over the analysis period. Needs are identified based on the guardrail group condition and decision criteria as described in section F.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. The deterioration and improvement matrix described in

this Appendix depicts the percent deterioration or improvement, depending if the guardrail system is in condition A, B, C, D, or F. The random function benefits from a generated number which is between 0 and 1 that illustrate the probability of moving from one condition category to another the next year. This number varies by each run for every section and based on the calculated probabilities for five different conditions, the next year condition has been chosen by this random number. The magnitude of deterioration and improvement is also obtained from the comparison of the base years. By identifying next year condition based on the random number and the magnitude of deterioration or improvement, the guardrail section condition is predicted for the next years. Table F-7 lists the costs per foot of guardrail for maintenance and replacement activities.

Table F-7. Costs of preservation activities for highway guardrail.

Parameter	Value	Source
Cost of guardrail maintenance (by lineal foot)	$7	Average cost to maintain, UDOT data
Cost of guardrail replacement (by lineal foot)	$103	Average cost to replace, USDA and TxDOT Bid Tabulations

Different maintenance activities take place depending on the damage and the deficient length of the guardrail system. In the example presented in this Appendix, the model considers that a certain percentage of the guardrail in condition B, C, D, and F receives maintenance as shown in Table F-8. Grades and activities described in the model are based on data analysis and expert knowledge. The maintenance and replacement activities are performed each year based on the grade that the guardrail section and the transition matrices previously described. The grading scale separates guardrail sections based on the percent deficient length of the guardrail section over the total length of the guardrail section, therefore, for guardrail sections in grade "C", 60 percent of the deficient guardrail section length receives some type of maintenance while 40 percent of the deficient guardrail section length receives replacements. For guardrail sections in grade "D", 20 percent of the deficient guardrail section length receives some type of maintenance while 80 percent of the deficient guardrail section length receives replacements. For guardrail section in grade "F", 100 percent of the deficient guardrail section length receives replacements. Lastly, there are not maintenance activities performed for guardrail section lengths in grade "A".

Table F-8. Guardrail system grading scale and preservation activities.

Percent Deficient	Grade	Activity
0.00-10.02	A	No Maintenance
10.03-20.01	B	100% Maintenance
20.02-30.00	C	60% Maintenance, 40% Replacement
30.01-39.99	D	20% Maintenance, 80% Replacement
40.00-100.00	F	100% Replacement

F.3 Step 3: Conduct Delayed Maintenance Scenarios Analyses

F.3.1 Formulate Delayed Maintenance Scenarios

Table F-9 describes the set of scenarios evaluated for guardrail systems. In Scenario 1, maintenance and replacement activities are performed with sufficient funds to implement the agency's preservation plan. The budget from this scenario is considered as the baseline budget. Scenario 2 evaluates the impact of "no

maintenance" on the future performance of the guardrail system and maintenance 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 guardrail group needs maintenance in year n then this activity is deferred by certain number of years. Delayed maintenance by limited budget is modeled by delaying maintenance activities until funds becomes available

Table F-9. Key elements to analyze delayed maintenance scenarios for guardrails.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 10 years	Results
Guardrail System Database with Inventory and Condition Assessment	Deterioration models based on transition condition probability matrices to model the increase/decrease in deficient guardrails.	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. 55 percent of baseline budget	Analytical Tools: Spreadsheet based model to perform scenario analyses Reports: • Impact on condition due to delayed maintenance • Agency costs over time • Changes in the Guardrail System Value and Sustainability Ratio

In the budget-driven scenario (Scenario 4), guardrail group priorities for funding allocation are based on a Maintenance Priority Index (MPI). MPI indicate the level of urgency for maintenance for a guardrail group and it is based on the annual average daily traffic (AADT), the length of the guardrail, and crash history records. The guardrail sections are ranked by the MPI from the highest to the lowest priority. The Dynamic Bubble-Up (DBU) method is used to allocate funds beginning with the guardrail group with the highest MPI until funds are exhausted (Chang 2007). Highway agencies may use different criteria and/or method to prioritize funding allocation. Guardrail groups in need of a maintenance or replacement, but delayed due to limited budget, are moved to a lower condition category. The transition condition matrices are used for deterioration or improvement.

F.3.2 Perform the Delayed Maintenance Scenarios Analyses

Table F-10 shows the 10-year agency costs, backlog in the last year of analysis, and the percentage of guardrail groups which are more than 40 percent of deficient length.

Table F-10. Summary of results for the scenario analyses for the guardrail system.

Scenario	Description	Total Agency Cost[1]	Backlog Cost[1]	Percent of Guardrail Groups with More than 40 percent Guardrail Deficient Length (Condition F)[1]
1	All Needs	$14.86 M	$0	8
2	Do Nothing	$0 M	$95.79 M	100
3	Delayed maintenance a. 1-year cyclical delay	$31.03 M	$23.56 M	71

	b. 3-year cyclical delay	$19.73 M	$59.69 M	98
	Budget-driven with limited funds			
4	a. 80 percent of baseline budget	$11.65 M	$30.84 M	38
	b. 55 percent of baseline budget	$7.96 M	$55.13 M	62

[1]At the end of the year 10.

In Scenario 1, the percentage of deficient guardrail reduces to 8 percent with an investment of $14.86 million over a 10-year period.

In Scenario 2, where no funding is available over the same period, the backlog cost increases to $95.79 million and 100 percent of the system reaches condition F at the end of year 10.

In Scenarios 3.a and 3.b, the agency costs increase due to delayed maintenance in comparison to Scenario 1. In Scenario 3.a, when maintenance activities are delayed by 1 year, agency costs are $31.03 million and $23.56 million backlogged, then 71 percent of the system is in condition F at the end of year 10. In Scenario 3.b, when maintenance activities are delayed by 3 years, agency costs are $19.73 million and $59.69 million backlogged, then 98 percent of the system will be in condition F at the end of year 10.

In Scenario 4.a, when maintenance activities are delayed due to limited budget, 80 percent of baseline budget, agency costs are $11.65 million and $30.84 million backlogged, then 38 percent of the system will be in condition F at the end of year 10. In Scenario 4.b, when maintenance activities are delayed due to limited budget, 55 percent of baseline budget, agency costs are $7.96 million and $55.13 million backlogged, then 62 percent of the system will be in condition F at the end of year 10.

F.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 base-line scenario from the needs analysis.

Consequences on the Guardrail System Condition

At the beginning of the analysis, 49 percent of the guardrail system is in condition A, 8 percent in condition B, 8 percent in condition C, 13 percent in condition D, and 22 percent in condition F as Figure F-3.

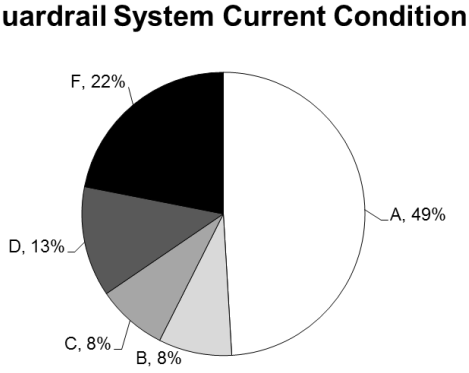


Figure F-3. Guardrail system current condition.

Figure F-4 shows the changes in condition categories under different scenarios during the analysis period. It is observed the impact in condition due to the delayed maintenance and the budgeting restrictions. Scenario 2 and Scenario 3.b look similar at the end of the year during the analysis period.

Figure F-5 shows the guardrail system condition at the end of the 10 years. In the ideal scenario of unlimited budget or baseline to address all needs, Scenario 1, there are only 8 percent of guardrails in condition F, while this condition group increases to 71 percent and 98 percent for 1 and 3-year delay scenarios respectively. In the Scenario 2 where no funding is available, 100 percent of the guardrails fall into the F category by year 10.

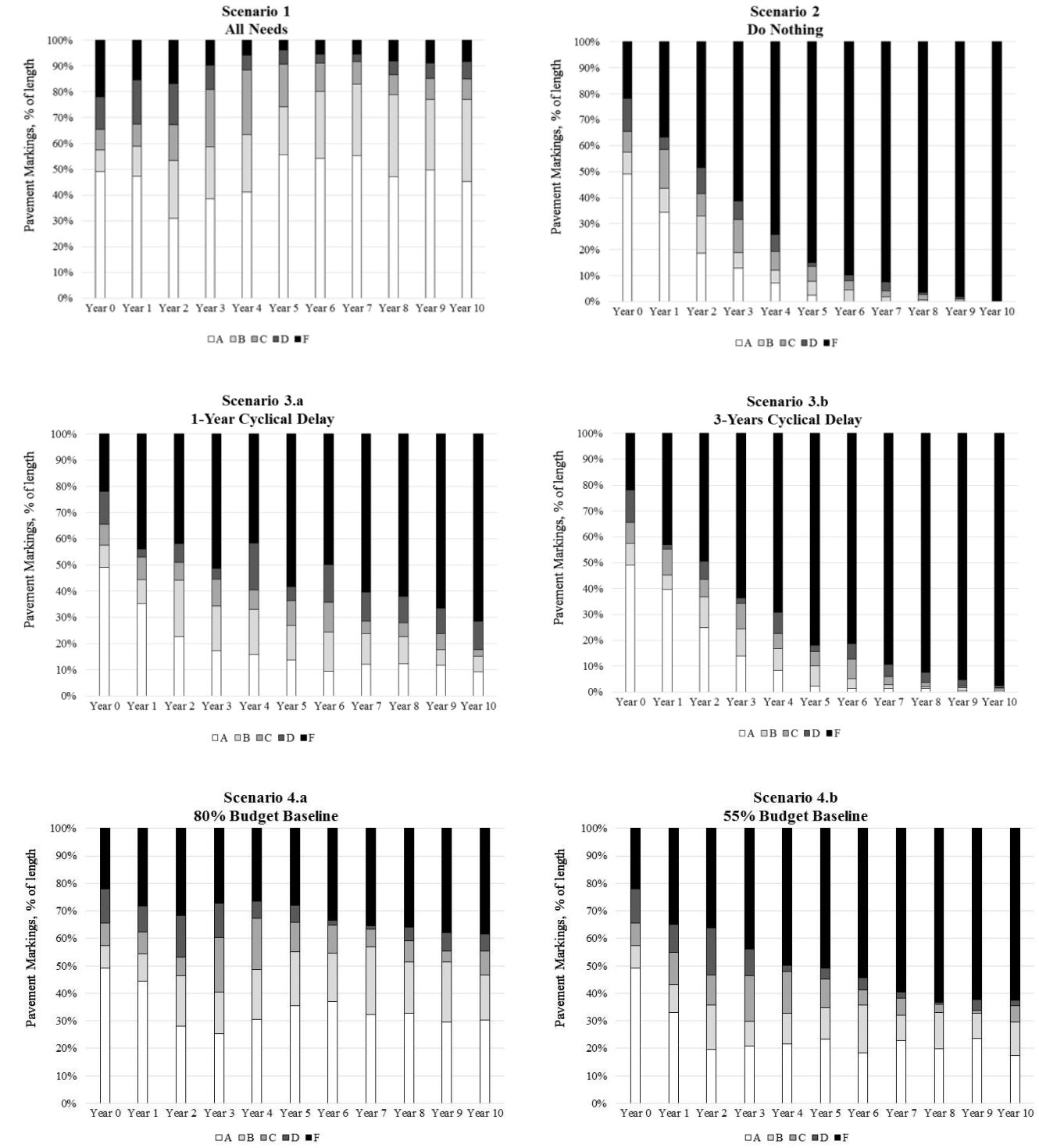


Figure F-4. Guardrail system condition categories over time, 10 years.

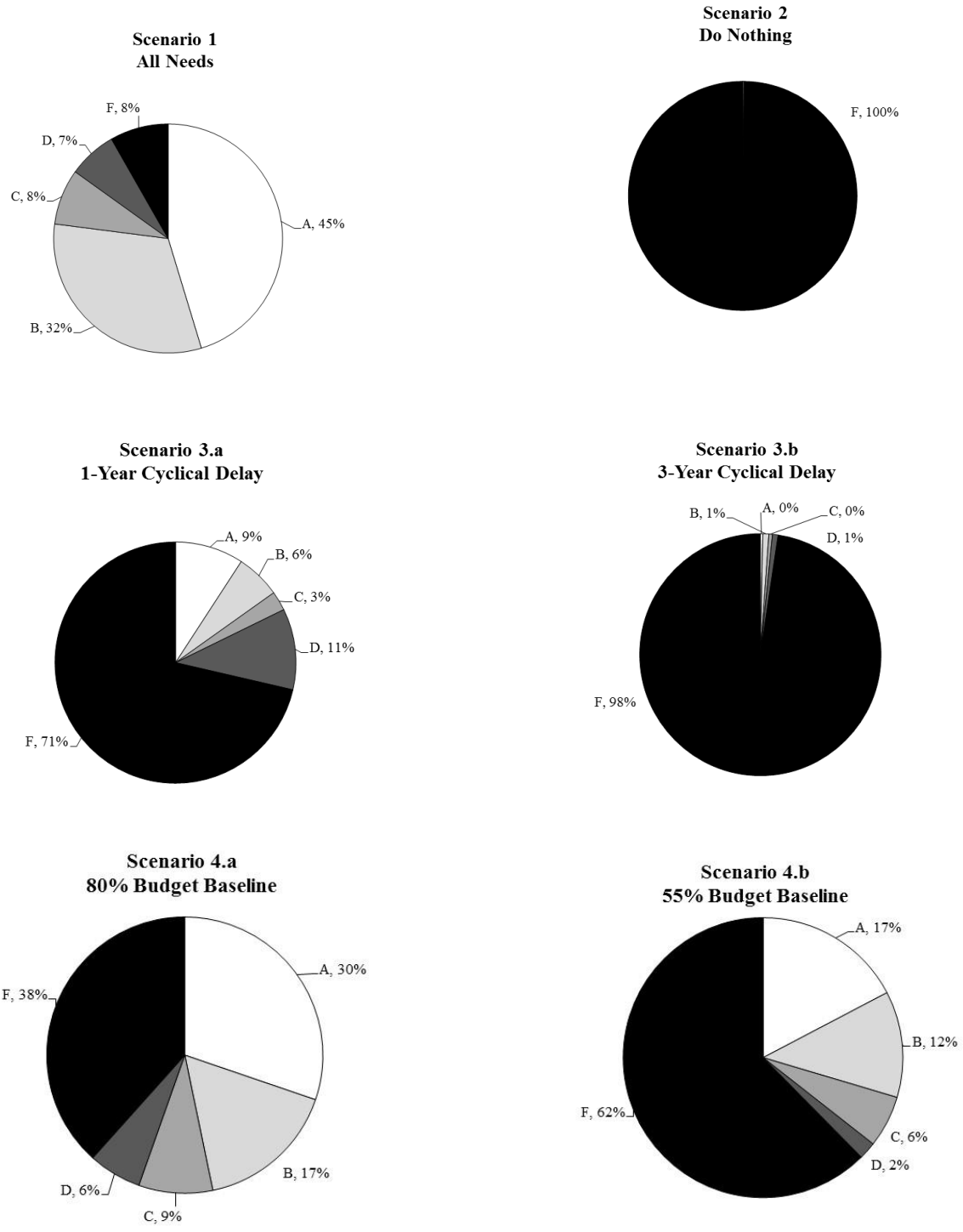
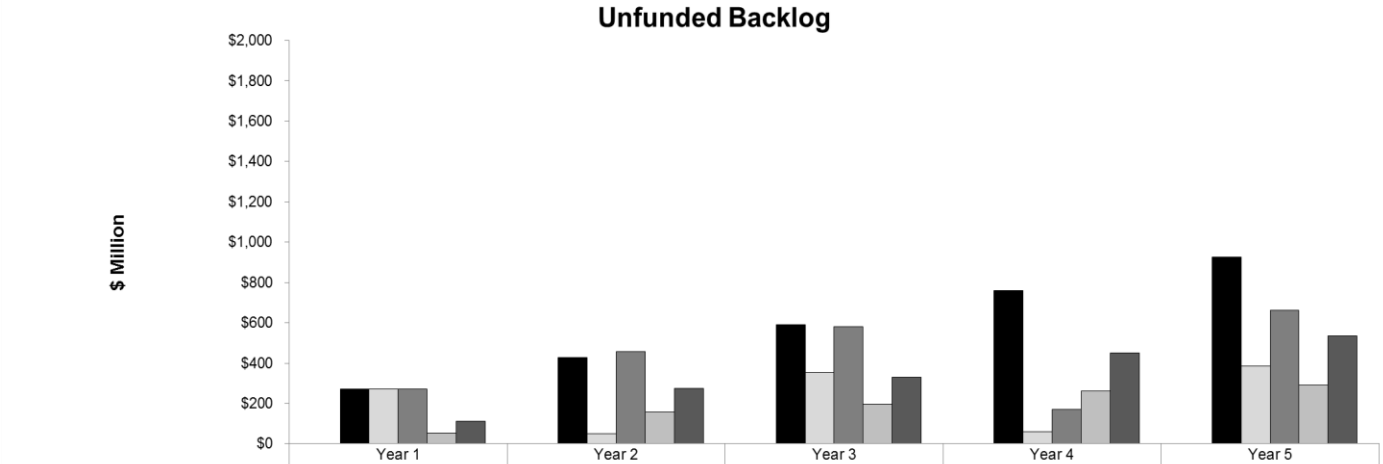


Figure F-5. Guardrail condition categories at the end of the analysis period, year 10.

Consequences on Future Budget Needs

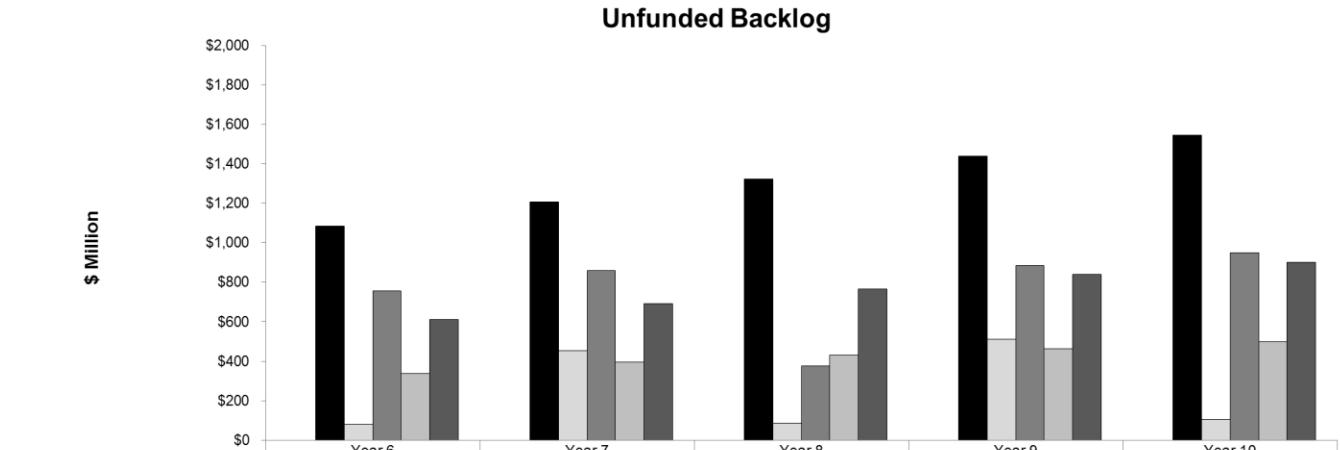
The budget for each scenario was tracked for each year and compared at the end of the analysis period. The maintenance and replacement costs are incorporated and are based on the preservation activities applied which is dependent on the grade that the guardrail system falls into each analysis year. Figures F-6 and F-7 show the unfunded backlog. The unfunded budget or backlog is about $2.72 million for scenario 2, do nothing, scenario 3.a and Scenario 3.b, delayed maintenance activities by 1 and 3 years respectively, while it is less than half of that for Scenario 4.b, 55 percent of baseline budget, and half a million dollars for scenario 4.a (80 percent of baseline budget).

At the end of the year five, the backlog for scenario 2, do nothing, grew to $9.27 million which is around three times as Scenario 3.a and Scenario 4.a. At the same year, 5, from beginning, Scenario 3.b has $6.6 million backlog that is more than $1 million backlog from Scenario 4.b. This trend fluctuates between second and third place at the year 10, while the highest backlog occurs in scenario 2 with $15.47 million, followed by $9.50 in Scenario 3.b, and $9.01 million in Scenario 4.b. The final backlog for Scenario 4.a, 80 percent of baseline budget, is roughly half a million with almost $1 million for scenario 3.a.



	Year 1	Year 2	Year 3	Year 4	Year 5
Scenario 1 - All Needs	$0.00	$0.00	$0.00	$0.00	$0.00
Scenario 2 - Do Nothing	$272.22	$429.04	$589.19	$758.72	$926.50
Scenario 3.a - 1-Year Cyclical Delay	$272.2	$51.3	$354.1	$59.6	$385.8
Scenario 3.b - 3-Year Cyclical Delay	$272.2	$455.5	$579.8	$171.0	$660.7
Scenario 4.a - 80% of Baseline Budget	$54.8	$156.2	$198.0	$261.3	$290.7
Scenario 4.b - 55% of Baseline Budget	$110.4	$274.0	$329.2	$450.8	$536.8

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



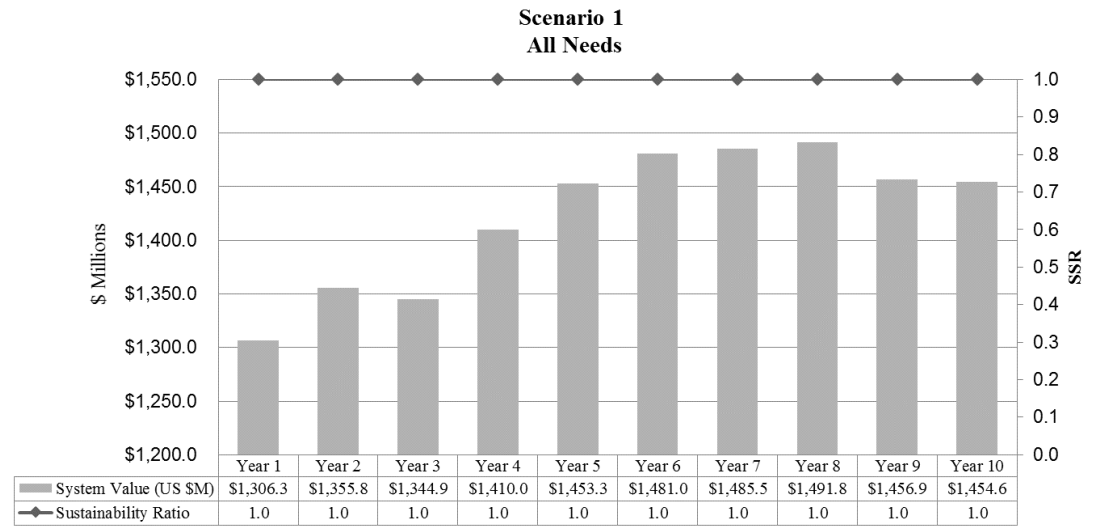
	Year 6	Year 7	Year 8	Year 9	Year 10
Scenario 1 - All Needs	$0.00	$0.00	$0.00	$0.00	$0.00
Scenario 2 - Do Nothing	$1,084.76	$1,206.84	$1,325.05	$1,440.62	$1,546.51
Scenario 3.a - 1-Year Cyclical Delay	$78.6	$452.0	$85.1	$511.1	$106.0
Scenario 3.b - 3-Year Cyclical Delay	$757.6	$859.8	$377.4	$885.8	$949.7
Scenario 4.a - 80% of Baseline Budget	$335.6	$395.4	$432.2	$461.6	$498.4
Scenario 4.b - 55% of Baseline Budget	$611.0	$693.0	$767.2	$839.4	$901.0

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

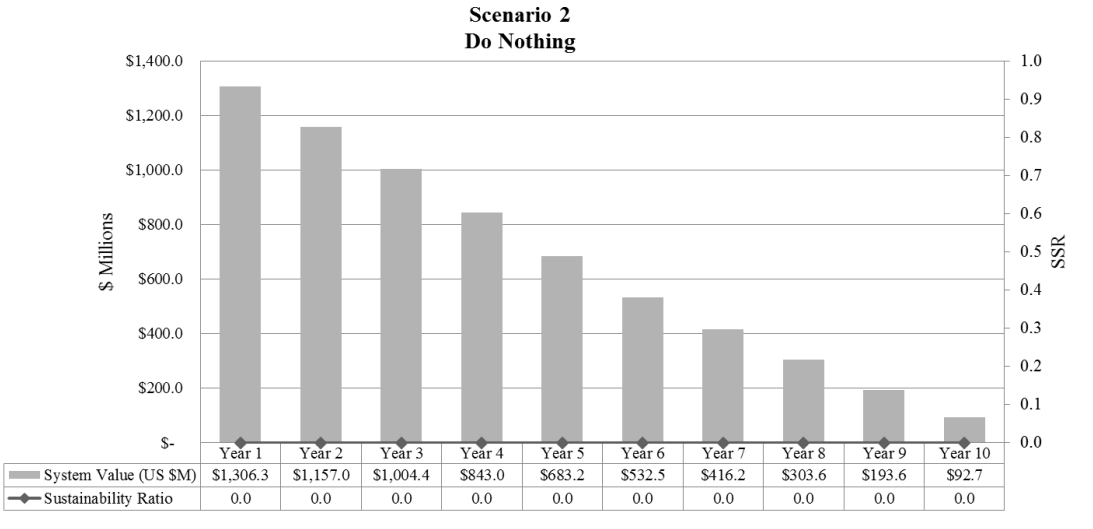
Changes on the Guardrail System Value and Sustainability Ratio

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

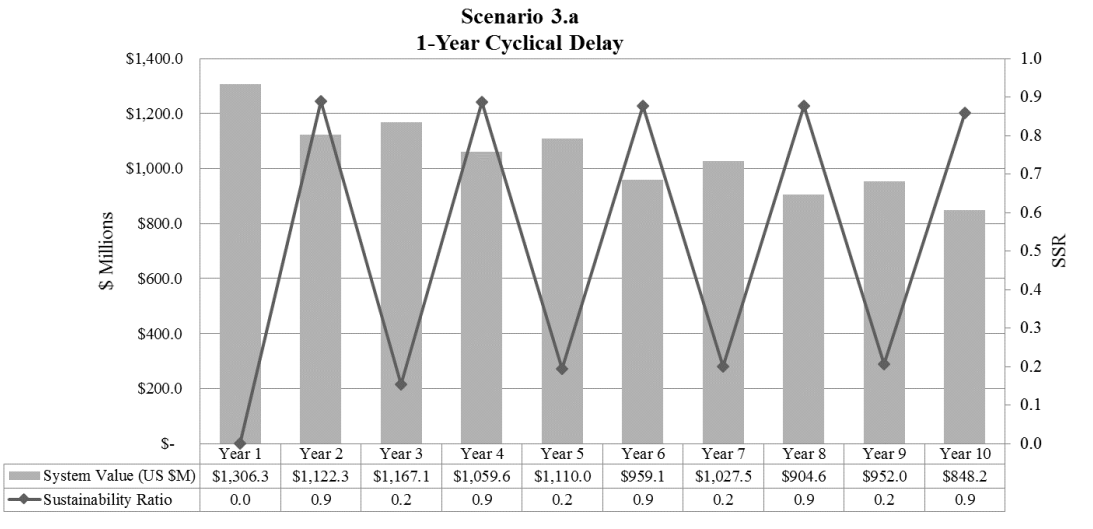
In the ideal situation of Scenario 1 (baseline), where all needed treatments are funded, the guardrail sustainability ratio (GSR) is 1. In the opposite situation, where no funding is available, the GSR is 0 during the analysis period. In scenario 3.a, the GSR is 0 at year 1 due to the funding delay and then fluctuates significantly between 0.2 and 0.9 within year two and year ten. In scenario 3.b, the GSR is 0 at years 1, 2, and 3 due to the funding delay and fluctuates between 0.1 to 0.8 within year 4 and year 10. The GSR fluctuations in scenario 3.a and 3.b are related to the delay and the changes in the condition between each year that are impacted by the delay. In budget limited scenarios the GSR is continuously declining as a result of limited funding. The largest decrease in system value can be seen in the Scenario 2 (Do Nothing), followed by Scenario 3.b (Delayed maintenance activities by 3 years) and Scenario 4.b (Budget-driven with 55 percent of baseline budget).



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,355.8	$1,344.9	$1,410.0	$1,453.3	$1,481.0	$1,485.5	$1,491.8	$1,456.9	$1,454.6
Sustainability Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

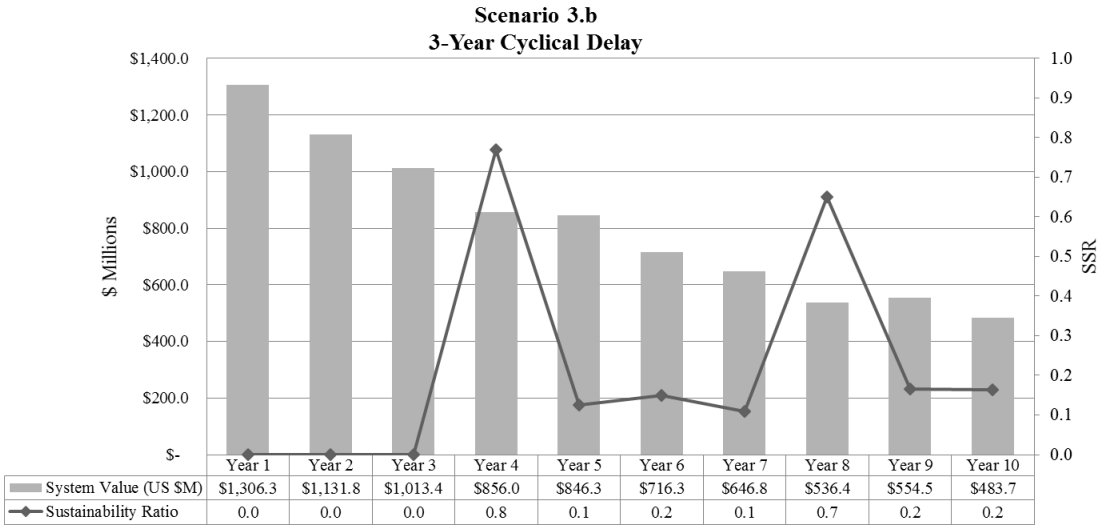


	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,157.0	$1,004.4	$843.0	$683.2	$532.5	$416.2	$303.6	$193.6	$92.7
Sustainability Ratio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

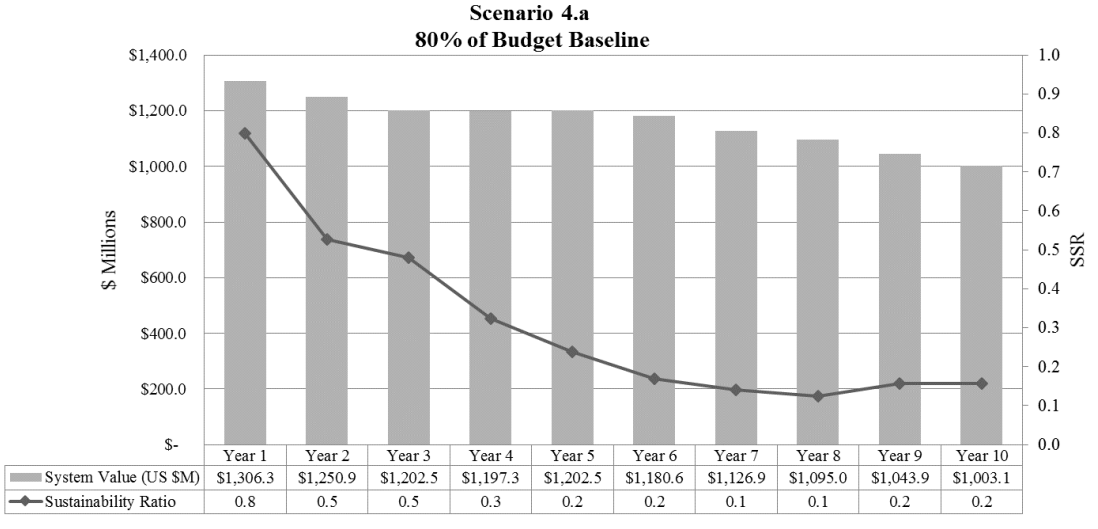


	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,122.3	$1,167.1	$1,059.6	$1,110.0	$959.1	$1,027.5	$904.6	$952.0	$848.2
Sustainability Ratio	0.0	0.9	0.2	0.9	0.2	0.9	0.2	0.9	0.2	0.9

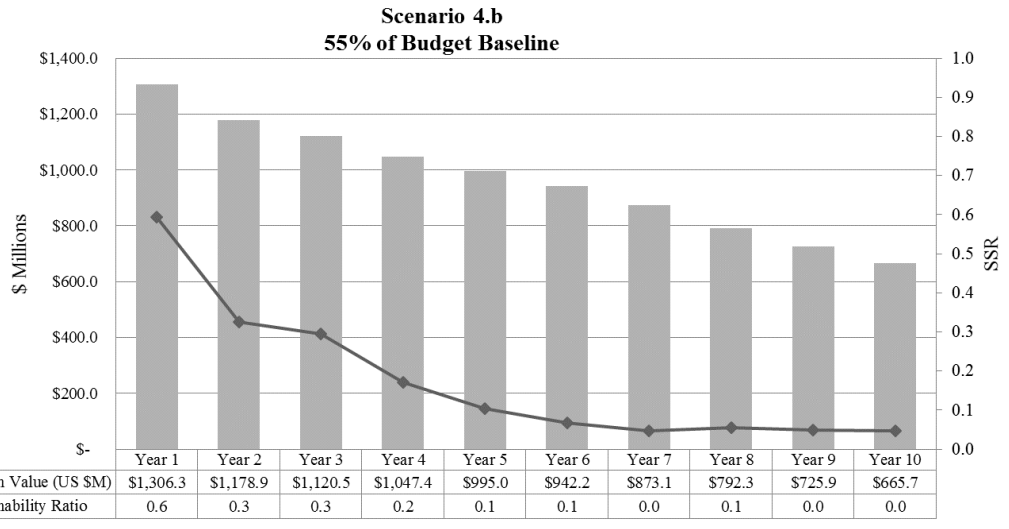
Figure F-8. Guardrail system value and sustainability ratio.



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,131.8	$1,013.4	$856.0	$846.3	$716.3	$646.8	$536.4	$554.5	$483.7
Sustainability Ratio	0.0	0.0	0.0	0.8	0.1	0.2	0.1	0.7	0.2	0.2



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,250.9	$1,202.5	$1,197.3	$1,202.5	$1,180.6	$1,126.9	$1,095.0	$1,043.9	$1,003.1
Sustainability Ratio	0.8	0.5	0.5	0.3	0.2	0.2	0.1	0.1	0.2	0.2



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
System Value (US $M)	$1,306.3	$1,178.9	$1,120.5	$1,047.4	$995.0	$942.2	$873.1	$792.3	$725.9	$665.7
Sustainability Ratio	0.6	0.3	0.3	0.2	0.1	0.1	0.0	0.1	0.0	0.0

Figure F-8. Guardrail system value and sustainability ratio. (Continued)

F.4 Summary

The scenario results that were summarized in Table F-10 in the previous section clearly demonstrate the effects of delaying needed maintenance to the guardrail system, affecting the condition and the agency costs of future work. Specific results for the case study include the following:

- Scenario 1, all needs, the total agency cost is $14.86 million and results in 8 percent of guardrail groups in condition F at the end of the 10 years.
- Scenario 2, do nothing, results in a cumulative backlog cost of $95.79 million and 100 percent of the guardrail system in condition F at the end of year 10.
- Scenario 3.a, maintenance activities delayed by 1 year, results in $31.03 million of agency costs for total work performed, and $23.56 million backlogged with 71 percent of the system in condition F at the end of year 10.
- Scenario 3.b, maintenance activities delayed by 3 years, result in $19.73 million of agency costs for total work performed, and $59.7 million backlogged with 98 percent of the system in condition F at the end of year 10.
- Scenario 4.a, 80 percent of baseline budget, results in $11.65 million of agency costs for total work performed, and $30.84 million backlogged with 38 percent of the system in condition F at the end of year 10.
- In Scenario 4.b, 55 percent of baseline budget, results in $7.96 million of agency costs for total work performed, and $55.13 million backlogged with 62 percent of the system in condition F at the end of year 10.

References

American Association of State Highway and Transportation Officials, Associated General Contractors of America, American Road & Transportation Builders Association (AASHTO-AGC-ARTBA) Joint Committee. 2006. *Asset Management Data Collection Guide*. Task Force 45 Report. American Association of State Highway and Transportation Officials, Washington, DC.

Chang, C. 2007. *Development of a Multi-Objective Strategic Management Approach to Improve Decisions for Pavement Management Practices in Local Agencies*. Dissertation. Texas A&M University, College Station, Texas.

Federal Highway Administration (FHWA). 2008. *W-Beam Guardrail Repair: A Guide for Highway and Street Maintenance Personnel*. Report No. FHWA-RT-90-001. Federal Highway Administration, Washington, DC.

Minnesota Department of Transportation (MnDOT). 2010. *Guardrail Replacement and Maintenance Guidelines*. Final Report. Minnesota Department of Transportation, St. Paul, MN.

Sicking, D. L., K. A. Lechtenberg, and S. Peterson. 2009. *Guidelines for Guardrail Implementation*. NCHRP Report 638. Transportation Research Board, Washington, DC.

South Carolina Department of Transportation (SCDOT). 2010. *Guardrail, Cable Barrier, and Crash Attenuator Inspection and Repair Guidelines*. South Carolina Department of Transportation, Columbia, SC.

Texas Department of Transportation (TxDOT). 2016. Letting and Bids. http://www.txdot.gov/business/letting-bids.html.

United States Department of Agriculture (USDA). 2013. Cost Estimating Guide for Road Construction. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5279284.pdf.

Utah Department of Transportation (UDOT). 2012. *Maintenance Management Quality Assurance Plus (MMQA+) Inspection Manual*. Utah Department of Transportation, Salt Lake City, UT.

Zimmerman, K. A. 2015. *Maintenance Quality Assurance Field Inspection Practices*. NCHRP Synthesis No. 470. Transportation Research Board, Washington, DC.