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# Asset Management Support Tools to Assist Agencies in the Development of Guardrail Preservation Programs

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ASSET MANAGEMENT SUPPORT TOOLS TO ASSIST AGENCIES IN THE  
DEVELOPMENT OF GUARDRAIL PRESERVATION PROGRAMS

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2017

## **Dedication**

This thesis is dedicated to my Mother and Father, Hilda and Rafael Gutierrez and my siblings, Stephanie and Michelle Gutierrez.

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DEVELOPMENT OF GUARDRAIL PRESERVATION PROGRAMS

by

SANDRA GUTIERREZ, EIT, BSCE

THESIS

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## **Abstract**

The purpose of this thesis is to develop a Guardrail Asset Management Framework and a Condition-Based Model to assist agencies in the development of guardrail preservation programs. Both of the guardrail asset management tools can be incorporated into an existing asset management program to assist agencies in utilizing guardrail inventory to forecast key asset management parameters such as the guardrail condition, funds necessary for maintenance and repair, backlogged funding, guardrail system value, and the guardrail sustainability ratio. Each of these parameters is described and determined for a case study involving six scenarios modeling funding and maintenance constraints that can arise in an asset management program.

The Guardrail Asset Management Framework is to be used as a guide, by state and local agencies, to determine key asset management objectives and practices that contribute to the use of the Condition-Based Model. The Condition-Based Model produces results that can be used to monitor the guardrail system. In monitoring the guardrail system, the agency can then adjust the asset management objectives and practices to better fit to the agency's goals and available resources. Utilizing the guardrail asset management tools can assist agencies in the development or advancement of their guardrail asset management and preservation programs.

## Table of Contents

Acknowledgements .....	v
Abstract .....	vi
Table of Contents .....	vii
List of Tables .....	ix
List of Figures .....	x
Chapter 1: Introduction .....	1
1.1 Background .....	1
1.2 Problem Statement .....	3
1.3 Research Objectives .....	5
1.4 Thesis Organization .....	5
Chapter 2: Literature Review .....	7
2.1 Asset Management Background .....	7
2.2 Asset Management Federal Programs .....	9
2.2.1 GASB-34 .....	9
2.2.2 Strategic Highway Safety Plan .....	11
2.3 Asset Management Principles .....	13
2.4 Performance Measures .....	15
2.5 Preservation Policies .....	18
2.6 Guardrail Standards .....	18
2.7 Roadside Safety .....	24
2.8 Guardrail Asset Management .....	26
2.8.1 Data and Inventory Collection .....	29
2.8.2 Guardrail System Performance Measures .....	32
2.8.3 Guardrail Service Life .....	34
2.8.4 Guardrail Deterioration and Damage .....	35
2.8.5 Guardrail Preservation Policies .....	38
2.9 Summary .....	41
Chapter 3: Guardrail Asset Management Framework .....	43
3.1 Background .....	43



3.2 Framework Description .....	45
3.3 Objective .....	46
3.4 Maintenance .....	48
3.5 Inventory .....	49
3.6 Condition-Based Model .....	50
3.6.1 Needs Analysis.....	50
3.6.2 Delayed Maintenance Analyses .....	50
3.7 Results.....	51
Chapter 4: Guardrail Condition-Based Model for Preservation Policy Development .....	53
4.1 Data Input.....	53
4.2 Condition-Based Maintenance Activities .....	54
4.3 Guardrail Transition Matrix .....	56
4.4 Increase and Decrease in Guardrail Length Deficiency .....	61
4.5 Scenarios Within the Model.....	64
4.6 Impacts of Guardrail Condition and Crash Rates .....	66
Chapter 5: Case Study - Application of the Guardrail Asset Management Framework.....	68
5.1 Condition-Based Model .....	68
5.2 Crash Cost Model .....	80
Chapter 6: Conclusion.....	86
6.1 Challenges.....	87
6.2 Framework Implementation.....	88
6.3 Future Research .....	89
References .....	92
Vita.....	95

## List of Tables

Table 2.1: Goals, Objectives, and Performance Measures used in a Transportation Planning Process .....	17
Table 2.2: UDOT Guardrail System Condition Grading Scale .....	33
Table 2.3: Guardrail Deterioration Condition Rate .....	35
Table 2.4: Guardrail Damage Classification Details .....	37
Table 3.1: Guardrail Objectives - Questions.....	48
Table 3.2: Guardrail Needs and Delayed Maintenance Scenarios.....	51
Table 4.1: Condition-Based Model - Maintenance Activity and Costs .....	54
Table 4.2: Percent Deficient Grade Scale .....	55
Table 4.3: Condition Transitions for Deterioration and Improvement .....	57
Table 4.4: Deterioration Transition between Year 1 and Year 2 .....	58
Table 4.5: Condition Transition Percentage per Total Sections .....	58
Table 4.6: Deterioration Transition Matrix.....	59
Table 4.7: Deterioration Transition Matrix Used for the Model .....	59
Table 4.8: Improvement Transition Matrix .....	60
Table 4.9: Improvement Transition Matrix Used for the Model .....	60
Table 4.10: Information to Determine Percent Increase in Deficient Guardrail Length .....	62
Table 4.11: Information to Determine Percent Decrease in Deficient Guardrail Length .....	63
Table 4.12: Condition Deterioration Transition Matrix.....	64
Table 4.13: Condition Improvement Transition Matrix .....	64
Table 4.14: Equations to Determine Total Crash Rate ( $R_s$ ).....	67
Table 5.1: Case Study Results .....	70
Table 5.2: Calculated Information to Determine the Total Crash Rate ( $R_s$ ).....	81
Table 5.3: Economic and Comprehensive Crash Costs .....	81
Table 5.4: Crash Cost and Associated Condition .....	82
Table 5.5: Guardrail Condition over the 10-Year Analysis.....	82
Table 5.6: Crash Rate for Each Condition .....	83
Table 5.7: Crash Cost for each Condition.....	83

## List of Figures

Figure 1.1: Guardrail.....	2
Figure 2.1: Generic Asset Management Process .....	15
Figure 2.2: Weak Post W-Beam Guardrail .....	19
Figure 2.3: Strong Post W-Beam Guardrail.....	19
Figure 2.4: Weak Post W-Beam Guardrail .....	20
Figure 2.5: Ironwood Aesthetic Guardrail .....	20
Figure 2.6: Box Beam (Weak Post) Guardrail.....	21
Figure 2.7: Blocked-Out W-Beam (Strong Post) Guardrail .....	21
Figure 2.8: Blocked-Out Thrie-Beam .....	22
Figure 2.9: Triangular Notched Steel Block-Out.....	23
Figure 2.10: Merritt Parkway Aesthetic Guardrail .....	23
Figure 2.11: Steel-Backed Timber Guardrail.....	24
Figure 2.12: Data, Functional, and Technology Components of a TAMIS.....	28
Figure 2.13: Screen capture from the NM RFI database for Guardrails.....	30
Figure 2.14: Guardrail Damage .....	36
Figure 2.15: Guardrail Damage. ....	36
Figure 2.16: Guardrail Damage .....	37
Figure 3.1: Relation between Decision-Making Levels .....	44
Figure 3.2: Guardrail Asset Management Framework .....	46
Figure 5.1: Data used in Transition Matrix and Case Study.....	68
Figure 5.2: Guardrail Condition at the Beginning of the Analysis .....	69
Figure 5.3: Scenario 1 (Left) and 2 (Right): Guardrail System Condition, Year 10 .....	71
Figure 5.4: Scenario 3a (Left) and 3b (Right): Guardrail System Condition, Year 10.....	72
Figure 5.5: Scenario 4b (Left) and 4b (Right): Guardrail System Condition, Year 10 .....	72
Figure 5.6: Scenario 1 (Left) and 2 (Right): Guardrail System Condition for each Year .....	73
Figure 5.7: Scenario 3a (Left) and 3b (Right): Guardrail System Condition for each Year.....	73
Figure 5.8: Scenario 4a (Left) and 4b (Right): Guardrail System Condition for each Year.....	74
Figure 5.9: Unfunded Backlog for each Scenario, Years 1 through 10.....	75
Figure 5.10: Scenario 1 – Guardrail System Value and Guardrail Sustainability Ratio.....	76
Figure 5.11: Scenario 2 – Guardrail System Value and Sustainability Ratio .....	77
Figure 5.12: Scenario 3a – Guardrail System Value and Guardrail Sustainability Ratio .....	78
Figure 5.13: Scenario 3b – Guardrail System Value and Guardrail Sustainability Ratio.....	78
Figure 5.14: Scenario 4a – Guardrail System Value and Guardrail Sustainability Ratio.....	79
Figure 5.15: Scenario 4b – Guardrail System Value and Guardrail Sustainability Ratio.....	80
Figure 5.16: Scenario 3a Crash Cost Results.....	84
Figure 5.17: Scenario 1 Crash Cost Results.....	85

# **Chapter 1: Introduction**

## **1.1 BACKGROUND**

To implement proactive guardrail asset management and preservation programs in agreement with current transportation asset management practices set in place, there are a number of parameters that need to be documented consistently for analysis. These parameters include inventory, guardrail condition, and assessment methods to forecast changes in the guardrail network condition over time. The current common practice within agencies involves replacing and/or repairing guardrails with major damage due to vehicular accidents. A proactive guardrail asset management program ensures that the agencies are consistently checking and maintaining guardrails so that the guardrail performs as it is intended to. This is important because the purpose of installing guardrails along the roadway is to mitigate the severity of potential accidents caused by errant vehicles leaving the roadway, and to provide a barrier between the vehicle and potentially hazardous areas (Fitzgerald, 2008). Guardrails can also be considered a roadside hazard, therefore proper design and placement significantly affect the intended performance which is to redirect vehicles or assist vehicles to come to a complete stop (Sicking et al., 2009). Guardrail refers to a barrier that is found along the roadway as shown in the figure below. A guardrail system refers to a large number of guardrails that agency is responsible for.

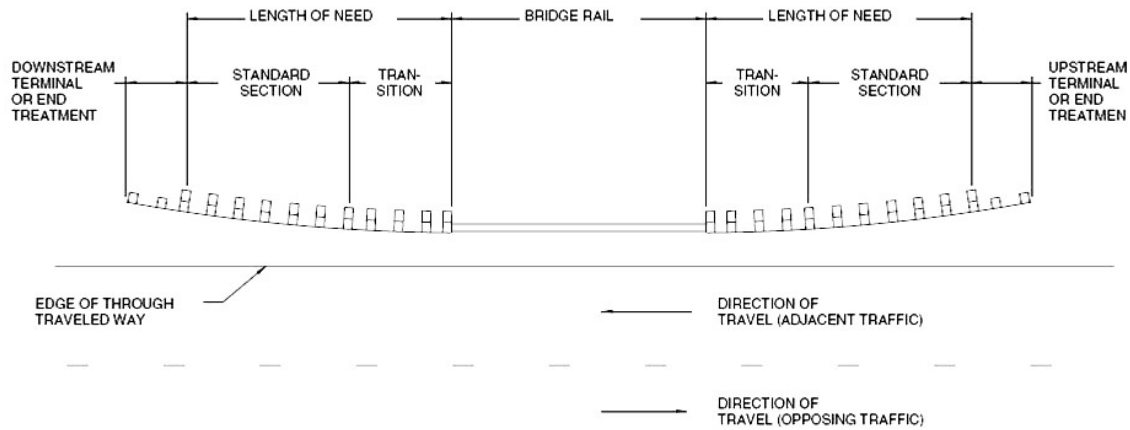


Figure 1.1: Guardrail

Source: Fitzgerald, W. J., 2008

The Roadside Design Guide classifies roadside guardrails as flexible, semi-rigid, or rigid and in total recognizes 23 types of guardrails that have been tested to meet MASH criteria and NCHRP 350 (AASHTO, 2011). The guardrail classification depends on the amount of deflection resulting from an impact. “Flexible systems are generally more forgiving than the other categories since much of the impact energy is dissipated by the deflection of the barrier and lower impact forces are imposed upon the vehicle” (AASHTO, 2011). This thesis focuses on the semi-rigid Blocked-Out W-Beam Strong Post guardrail which is one of “the most widely used barrier,” (Fitzgerald, 2008) and is simply referred to as guardrail throughout the thesis. Based on information received from Seattle Department of Transportation (SDOT), via email, the W-beam guardrail is the most commonly used guardrail type within the SDOT agency. SDOT mentioned that the reason for this is due to the cost, familiarity of staff with the installation, and because of the ease associated with storing the material.

A Guardrail Asset Management Framework and Condition-Based Model are presented in the thesis. The framework organizes asset management elements to consider in managing the guardrail system. Agencies can use the framework to determine their guardrail system objectives, and key elements that impact maintenance and repair, how the inventory is to be collected, the model scenario to be used, and the results provided by the model. The framework can be used

within a short-term or long-term plan and can be modified as the guardrail system is monitored. The Condition-Based Model is listed within the framework and is directly impacted by the agency's decisions made regarding the elements provided in the framework.

Funding and maintenance constraints are used to model scenarios that agencies may have to deal with as funding and resources become available. The availability of funding and resources result in agencies making decisions regarding the management of their assets. It is for this reason that the Condition-Based Model considers six scenarios that provide independent results for each scenario. This allows the agency to forecast parameters, dependent on the scenario, to better guide their decision-making. The intended purpose of the Guardrail Asset Management Framework and Condition-Based Model is to assist agencies in consistently monitoring their guardrail system to determine network level parameters such as guardrail condition, funds necessary for guardrail maintenance and repair, backlogged funding, guardrail system value, and the guardrail sustainability ratio over a 10-year analysis period. Each of these network level parameters is described and determined in a case study provided in Chapter 5.

## **1.2 PROBLEM STATEMENT**

A major challenge currently being dealt with in transportation infrastructure management is effectively allocating the limited resources across all transportation infrastructure assets. Other significant challenges include project prioritization, resource availability such as people, material and equipment, time management, and most importantly the ability to predict relevant factors that affect the infrastructure in the way that it is designed, developed, and maintained. There is a lack of fully structured asset management programs and preservation policies for many highway safety assets. Through recent mandated policies, asset management programs are required for all assets. The asset management programs are to incorporate data collection, data storage, and data analysis to be used for decision-making at the strategic, network, and project management levels.

Within the past five years, many highway agencies have established inventory databases for highway safety assets which are considered “non-traditional” assets. It is for this reason that

data are relatively new and may be inconsistent (Ford et al., 2012). It was determined that currently, complete historical guardrail data are not available for many agencies. This resulted as a challenge in utilizing the Condition-Based Model in the case study due to data and information gaps.

Financial issues related to infrastructure assets stem from the increasing population and the limited State Highway Funds. This has created a “transportation crisis” that endangers the quality of life and economic growth (Chang-Albitres et al., 2012). There is a need for consistent guardrail asset management and preservation programs that include periodic evaluation of the guardrails. Effective and efficient guardrail assessment and data collection can be used in the Condition-Based Model. The Condition-Based Model results can assist agencies in achieving their guardrail system goals by concluding if the objectives, and practices, set by the agency, are being met. If the goals are being achieved, then the agency can decide to adjust the guardrail evaluation and data collection which can result in resource savings. If the goals are not being achieved, then the agency will have to consider adjusting their guardrail asset management practices. Overall, the forecasting results can play a role in achieving goals and effectively funding timely maintenance and repair activities by providing results that adhere to the agencies decision regarding the framework elements.

Also, due to the limited funds, guardrails are not always maintained at the “as-built” conditions. Agencies focus on repairing guardrails that have sustained major damage that has impacted the guardrails safety performance, resulting in a detrimental effect on the roadway user. Replacement of guardrails or sections within the guardrail is performed in the event of a high severity crash. Minor guardrail damage is more common and results from low-speed collisions and during “routine highway maintenance operations, including snowplowing, mowing or paving, and exposure to the environment, which may result in corrosion or termite damage” (Gabler et al., 2010).

### **1.3 RESEARCH OBJECTIVES**

The primary objective of this thesis is to develop guardrail asset management support tools. The guardrail asset management support tools are an asset management framework and a Condition-Based Model. In developing the guardrail asset management support tools, existing guardrail asset management practices are identified and documented. Existing guardrail and general asset management practices are used as the foundation for the development of the tools in order to develop asset management support tools that can easily be incorporated into an existing asset management program. This will ensure that the development of the support tools takes into account guardrail asset management practices currently being considered. The framework also proposes additional steps or practices that can be incorporated into existing practices.

The support tool goals are to help agencies in making decisions but also to consider the limited agency funds to support data collection and guardrail system monitoring. In trying to achieve these goals, the Condition-Based Model uses basic guardrail inventory as the model input.

### **1.4 THESIS ORGANIZATION**

This thesis presents findings, results and conclusions for the Guardrail Asset Management Framework and the condition based model.

Chapter 1 introduces the importance of developing and integrating guardrail asset management tools into existing asset management programs as well as briefly discussing the problems associated with the absence of support tools. Current asset management challenges and objectives are presented as well.

Chapter 2 provides an extensive literature review focusing on asset management, federally mandated programs, asset management principles, performance measures, and preservation policies followed by guardrail related asset management elements. The guardrail related asset management elements include guardrail standards, roadside safety, and guardrail



asset management (which includes performance measures, service life, deterioration and damage, and preservation policies).

Chapter 3 defines the Guardrail Asset Management Framework. Background information and description of the framework elements are discussed.

Chapter 4 describes the development of the guardrail Condition-Based Model. The input data, maintenance activities, transition matrices are each defined and discussed.

Chapter 5 provides a case study that utilizes the guardrail Condition-Based Model. Case study results are provided and analyzed.

Chapter 6 provides the thesis conclusion. The conclusion provides the following sections: challenges, framework implementation, and future research.

## **Chapter 2: Literature Review**

The following sections define and provide information regarding existing asset management, asset management principles and policies, performance measures and asset management preservation policies. The second part of the literature review focuses on providing background information for guardrails and guardrail asset management. In discussing existing guardrail asset management, data collection, performance measures, service life, deterioration and guardrail preservation policies are further discussed.

### **2.1 ASSET MANAGEMENT BACKGROUND**

Asset management (AM) provides a strategic framework for the infrastructure management decision-making process in maintaining, upgrading and operating assets cost-effectively. AM includes a set of principles, concepts, and techniques used by agencies as part of their already available procedures in making decisions about resource allocation, use, and condition. AM is currently in the preliminary stages for consistent implementation across the United States and around the world. Department of Transportation (DOT) agencies have different asset management programs that have been developed to align with their objectives and available resources. The research and the development of the support tools, to further develop asset management programs, serves as progress towards guiding the efforts for cost-effective and efficient asset management programs, and preservation policies that extend across all transportation assets.

The Nation's transportation agencies primarily focused on building and expanding the Interstate Highway System at the beginning of the 1960s through the early 1980s. After 40 years of new highway construction, the Interstate Highway System was completed. During the late 1990s the focus shifted to the critical aspect of service life, maintenance management, and reconstruction of the existing infrastructure. Agencies realized that the "\$1 trillion investment in highways and bridges" required a concept and practice to monitor important infrastructure parameters such as detailed inventory; location, date of recent maintenance, inspection and

rehabilitation, current guardrail condition, and expected performance (FHWA, 1999). In 1999, the American Association of State Highway and Transportation Officials (AASHTO) created a Planning Subcommittee, and the Federal Highway Administration (FHWA) established an Office of Asset Management to discuss and develop AM guidelines for highway and bridge infrastructure asset management. Through the early 21<sup>st</sup> Century, agencies collected data but lacked a strategic and systematic approach to preserve and maintain the assets. This resulted in limited discussion regarding life-cycle costs.

In 2003, the focus shifted to identifying assets within each agency along with documenting the condition of the assets. Some agencies had the resources to develop and analyze condition trends with the data collected but still lacked a strategic and systematic approach for asset management decision-making. In 2011, AASHTO released the AASHTO Guide for Implementation for Asset Management to assist agencies in fully implementing asset management for pavements and bridges. In 2012, Congress signed the Moving Ahead for Progress in the 21<sup>st</sup> Century Act (MAP-21), which mandated agencies to consider long term planning. States were required to address pavements and bridges initially but were encouraged to include all infrastructure assets. State agencies were mandated to think about the following:

- Strategic and systematic approaches
- Inventory and conditions
- Objectives and measures
- Performance gap identification
- Life-cycle cost
- Risk management analysis
- Financial plans
- Investment strategies
- Preservation

MAP-21 was one of many policies to mandate agencies to adjust its asset management approach to achieve a thought out and systematic business approach. The following section discusses asset

management federal programs that support the development of asset management programs and legally mandate agencies to develop or incorporate specific asset management practices into its existing programs.

## **2.2 ASSET MANAGEMENT FEDERAL PROGRAMS**

The following asset management programs are listed chronologically and provide information that highlights the importance and impact that has resulted from the programs. The first FHWA mandated program to be discussed is the Governmental Accounting Standards Board 34, followed by the Strategic Highway Safety Plan which includes the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, the Moving Ahead for Progress in the 21<sup>st</sup> Century, and the Fixing America's Surface Transportation Act.

### **2.2.1 GASB-34**

In June 1999, the Governmental Accounting Standards Board (GASB) published Statement 34, "Basic Financial Statements and Management's Discussion and Analysis for State and Local Governments," known as GASB-34. GASB-34 was developed to make annual reports easier to understand and more useful to the people who use governmental financial information. Following accounting principles, GASB-34 requires agencies to report their capital assets including initial construction costs and subsequent costs of capital improvements or any associated expenses to operate the assets. Agencies must follow GASB-34 standards to earn clean audits. Failure to comply with the GASB-34 requirements may result in difficulties in receiving federal funding or reduced bond ratings (FHWA, 2000).

GASB-34 considers two methods to assess the change of the infrastructure assets dollar value over time. The two methods include the depreciation method and the modified approach. Historical cost depreciation is calculated by distributing the net cost of the assets over their service life, in which the net cost is obtained by subtracting the estimated salvage value at the end of the service life from the historical cost. Straight line, declining balance, or any other acceptable depreciation method can be used and tied to a depreciation schedule. On the other

hand, agencies following the GASB-34 modified approach are required to implement an asset management system and include a discussion and analysis section in their reports addressing the following:

1. Significant changes in the assessed condition of eligible infrastructure assets from previous condition assessments.
2. How the current assessed condition compares with the condition level the government has established.
3. Any significant differences for the estimated annual amount to maintain or preserve eligible infrastructure assets compared with the actual amounts spent during the current period.

Recommendations from GASB-34 could be expanded to provide the following information regarding the impact of maintenance strategies in highway asset condition:

1. Condition of assets versus the cost of maintenance to ensure that infrastructure assets will reach their useful life while providing the desired level of performance.
2. Condition of assets versus the cost of preservation to extend the life of infrastructure assets beyond its original useful life, but not increase the capacity or efficiency of the asset performance.

Information regarding asset deterioration significantly improves the efforts in developing and implementing an asset management system. Asset deterioration plays a major role in effectively allocating funds and in determining maintenance practices. A high deterioration rate requires a higher frequency of maintenance to be considered in the asset management program. This affects the budget and necessary resources. When the deterioration is low, there is a need for less frequent maintenance and requires less budget and resources. Either situation requires evaluation and consideration when modifying or developing an asset management program because the short and long term planning can be significantly affected.

### **2.2.2 Strategic Highway Safety Plan**

In 2005, states were required to develop a Strategic Highway Safety Plan (SHSP). All states complied by October 1, 2007. “As the states implement their plans, they are gathering information for the evaluation of the plan, and the results from the evaluation will guide the update process showing where changes are needed in the future” (FHWA, 2016). The SHSP provides a “comprehensive framework for reducing traffic-related fatalities and serious injuries across all modes, and on all public roadways” (FHWA, 2016). The plan provides an opportunity to develop common statewide goals and priorities; data, knowledge and resource sharing, to name a few. SHSP promoted the development of a performance-based approach for decision-making. The following asset management policies were developed under Strategic Highway Safety Plan (SHSP).

#### **SAFETEA-LU**

The Safe, Accountable, Flexible, Efficient Transportation Equity Act: a Legacy for Users (SAFETEA-LU) was signed into law on August 10, 2005, by President George W. Bush. This plan addresses targeted investment items including safety, equity, innovative finance, congestion relief, mobility and productivity, efficiency, environmental stewardship, and environmental streamlining. SAFETEA-LU provides the funds that are needed to “maintain and grow our vital transportation infrastructure” (FHWA, 2005).

#### **MAP-21**

The Moving Ahead for Progress in the 21<sup>st</sup> Century Act (MAP-21) is a government based program, as well as a major milestone in the development of asset management that was developed and set into action for the purpose of improving funding for transportation infrastructure programs.

MAP-21 was signed into law on July 6, 2012, by President Barak Obama. It was the first long-term enacted program within the Strategic Highway Safety Plan (SHSP) and was a step forward in the U.S. economy (FHWA, 2012). MAP-21 was established for the purpose of guiding the growth and development of transportation infrastructures by transforming the policy

and programmatic framework of investments. The program establishes performance goals for Federal Highway programs at the national level. The following are U.S. transportation system challenges that are addressed in MAP-21:

1. Improving safety – The goal is to reduce traffic fatalities and serious injuries on all public roads.
2. Maintaining infrastructure condition – To maintain the highway infrastructure asset system in order to have the infrastructure in a state of good repair.
3. Reducing traffic congestion – To decrease congestion by a significant amount on national highway systems.
4. Improving efficiency of the system and freight movement – The primary goal is to “strengthen the ability of rural communities to access national and international trade markets and support regional economic development” through freight network improvements.
5. Protecting the environment – To protect and enhance the environment by achieving higher transportation system performance.
6. Expediting project delivery – To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies’ work practices (FHWA, 2012).

Map-21 was enacted to facilitate agencies in creating plans, establishing targets, and reporting on the condition of their infrastructure systems.

### **FAST Act**

The Fixing America’s Surface Transportation Act (FAST Act) was signed into law on December 4, 2015, by President Barak Obama. This Act maintains the focus on safety goals. The FAST Act is mandated through the year 2020 with a total amount of \$305 billion that was initiated in 2016. The results expected from the FAST Act are to provide an opportunity for state

and local governments to propose and construct critical transportation projects (FAST, 2015). A critical transportation project is a project that enhances at least one of the following: safety, traffic congestion, the efficiency of freight movement, or the environment.

As highlighted in the asset management policies, there is guidance to support agencies in what needs to be achieved in its asset management programs. The allocated funding also assists agencies to determine if its key projects meet any requirements to receive federal funding. Whether agencies have been mandated to develop or modify their asset management (AM) programs, the intent is to not only efficiently and proactively help agencies to manage its asset but also to enhance the safety of the public and protect the environment.

The following section discusses AM principles that are considered and adhered to in the development of an AM program.

### **2.3 ASSET MANAGEMENT PRINCIPLES**

AM provides a strategic framework for infrastructure management that assists agencies in utilizing their available resources effectively and efficiently (NCHRP, 2006). AM includes a set of principles, concepts, models, and techniques that can be used by agencies as part of their current procedures to effectively make decisions about resource allocation to achieve their infrastructure performance objective. The following, provided in “Performance Measures and Targets for Transportation Asset Management,” are the foundation of AM principles:

1. **Policy-Driven** – Resource allocation decisions are based on a well-defined and explicitly stated set of policy goals and objectives. These objectives reflect desired system condition, the level of service, and safety provided to customers that are typically tied to economic, community, and environmental goals.
2. **Performance-Based** – Policy objectives are translated into system performance measures that are used for both day-to-day and strategic management.
3. **Analysis of Options and Tradeoffs** – Decisions on how to allocate resources across different assets, programs, and types of investments are based on understanding how



different allocations will affect the achievement of policy objectives and the best options to consider. The limitations posed by realistic funding constraints also must be reflected within the range of options and tradeoffs considered.

4. **Decisions Based on Quality Information** – The merits of different options with respect to an agency’s policy goals are evaluated using credible and current data. Decision support tools are applied to help in accessing, analyzing, and tracking the data.
5. **Monitoring to Provide Clear Accountability and Feedback** – Performance results are monitored and reported for both impacts and effectiveness. Feedback on actual performance may influence agency goals and objectives, as well as future resource allocation and use decisions (NCHRP, 2006).

These principles are used to develop performance measures considered in an AM program by transportation agencies. AM is an evolving concept and assists transportation agencies to “monitor the transportation system and optimize the preservation, upgrading, and timely replacement of highway assets through cost-effective management, programming and resource allocation decisions” (FHWA, 1999). Transportation agencies understand that AM is vital when resources are limited. The limited budget requires decision-making models and support tools that involve scheduling and the allocation of funds across infrastructure assets. Not only are the decisions necessary for timely infrastructure maintenance activities but it is also highly political in some cases and are susceptible to increased public scrutiny. Figure 2.1 shows a general asset management process that highlights the previously discussed items.

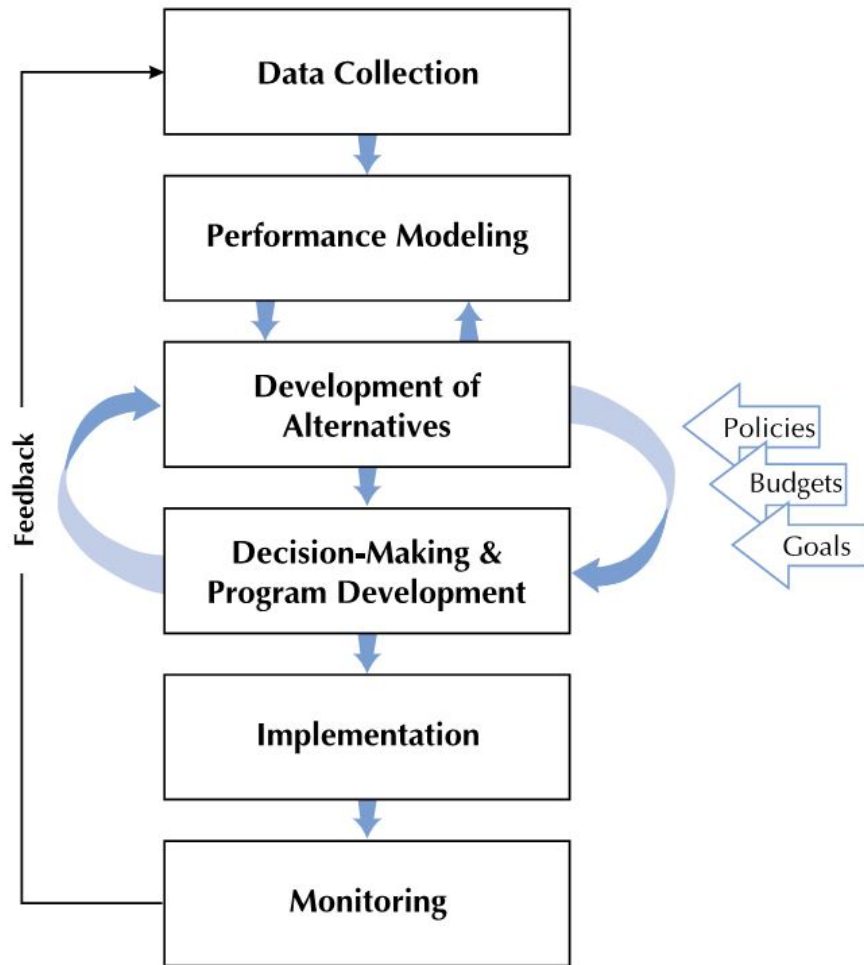


Figure 2.1: Generic Asset Management Process

Source: AASHTO, 1997

By following asset management practices, as shown in Figure 2.1, an agency can better understand the asset performance to develop a preservation program to achieve goals and lengthen the life-cycle of the infrastructure.

## 2.4 PERFORMANCE MEASURES

The federal government has steered transportation planning agencies towards adopting performance-based planning by making specific performance measures mandatory through MAP-21. There is an increase for positive outcomes when investments involve public money. It is for this reason that transportation agencies have been adopting performance-based planning processes to guide them towards making investment decisions.

Transportation Performance Measurement is a strategic approach “that uses system information to make investment and policy decisions to achieve national, regional, or even local performance goals” (FHWA, 2013). Performance measures are linked to a program’s goals and objectives. The Performance Measure System also provides continuous measurement and monitoring which provides feedback that is used to determine if the established long-term goals and objectives are being met. The feedback and results from the asset Performance Measure System assists in improving public confidence towards government officials. The Performance Measurement System varies between each of the agencies due to resources and funding availability, but most contain the same elements. According to “Performance Measurement for Transportation Infrastructure: The Paradigm for Transportation Planning in the 21st Century,” the following is used to develop objectives (Heller, 2014):

1. Develop an overall vision and a set of goals.
2. Develop specific objectives that flow directly from goals. These objects should be measurable and clearly define desired outcomes to help achieve the goals.

From these objectives, performance measures are developed. A performance measure should have the following characteristics (Heller, 2014):

1. Be acceptable and meaningful to the customer (user).
2. Be able to easily convey how well the goals and objectives are being met.
3. Be simple, understandable, logical, and repeatable.
4. Show a trend.
5. Be supported by data that is fairly easy to obtain.
6. Be timely.

The primary purpose of performance measures is to be able to determine if and how well the goals are being achieved. Table 2.1 shows an example of goals, objectives, and performance measures that were developed for a transportation planning process.

Table 2.1: Goals, Objectives, and Performance Measures used in a Transportation Planning Process

Goals	Objectives	Performance Measure
Mitigate Traffic Congestion	Reduce average vehicle delay on major arterials	Average Vehicle Delay (sec.)
Improve Transportation Safety	Reduce Fatalities per 100 million VMT	Crash Rate (No. of Crashes/Mile)
Promote Transportation Choices	Increase bike ridership	Miles of Bike and Pedestrian Paths

Source: Heller, D. S., 2014

At the national level, transportation performance measures are mainly focused on safety, infrastructure condition, freight mobility, economic vitality, and livability. Due to the importance of maintenance activities, and the direct impacts on asset performance, maintenance quality assurance (MQA) programs were developed. The first MQA programs were developed in the 1990s and mainly focused on documenting work accomplishments, allocated resources, production rates, and comparing planned versus actual accomplishments. During the past decade, MQA programs have “become more customer-oriented, with an increased focus on maintenance outcomes and targeted performance levels” (NCHRP, 2012). State highway agencies have used their MQA results to develop performance targets and estimate budget necessary to be used towards maintenance and replacement activities. Establishing performance targets allows agencies to monitor their assets in order to make decisions about the additional funds and resources that may be needed if their performance targets are not achieved.

MQAs are not federally mandated therefore each state has established a program adapted to its needs and not to national standards. This has resulted in states rating its assets as passing or failing, or with a level of service (LOS) grade (e.g., A, B, C, D, or F) to state how close the asset is to failing. LOS and numerical ratings are performance targets that are “expressed as a tangible, measurable goal against which achievement can be compared” (NCHRP, 2015). As listed in NCHRP 470, Maintenance Quality Assurance Field Inspection Practices, performance measures

are quantifiable measures “of performance to determine progress toward specific, defined organization objectives based on statistical number evidence” (NCHRP, 2015). Example performance measures include the percent of damage of a guardrail and the percent of guardrails below standard. The following sections discuss AM preservation policies.

## **2.5 PRESERVATION POLICIES**

Preservation policies are developed for the purpose of extending the life of an asset by applying the correct treatment at the right time. Preservation of infrastructure enables state highway agencies to provide “safe, smooth, and sustainable transportation systems” (NCHRP, 2012). The previously discussed AM policies have provided an opportunity for agencies to continue their efforts in developing preservation policies and strengthening their AM programs to include all assets within their transportation infrastructure.

According to a Preservation Project Scope of Work Memorandum for Washington State Department of Transportation (WSDOT), a new sign and guardrail management strategy was being evaluated to develop a strategic approach for preserving highway safety assets and making spot safety improvements. Their motive in looking further into this matter was to “maximize the cost-effectiveness of replacing these assets and optimize their operational life span” (WSDOT, 2012).

AM, AM policies and principles, performance measures, and preservation policies were previously discussed in a general asset management context. The following sections transition the literature review into guardrails and introduce the following: guardrail standards and background, history of roadside safety, and guardrail AM.

## **2.6 GUARDRAIL STANDARDS**

Different documents refer to guardrails as barriers, roadside barriers, highway barriers, safety barriers or traffic barriers. This research focuses on longitudinal guardrails that are placed along the roadside for the purpose of protecting motorists from colliding with obstructions along the roadside and from taking a dangerous, off-roadway path “where recovery of vehicle control

is not reasonably possible” (AASHTO, 2011). The guardrail components are shown in Figure 2.2 and Figure 2.3.

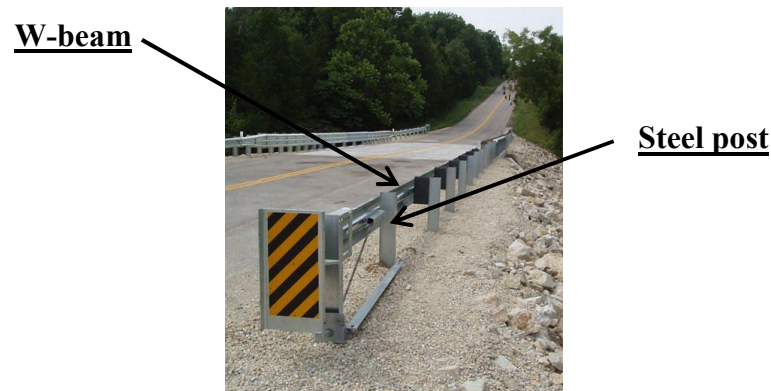


Figure 2.2: Weak Post W-Beam Guardrail

Source: Engineering Policy Guide, 2017



Figure 2.3: Strong Post W-Beam Guardrail

Source: Corral Sales Co., 2014

Guardrails are categorized as flexible, semi-rigid, or rigid. This categorization is based on the deflection experienced on impact. There are numerous types of guardrails that have met the required testing specifications described in MASH and NCHRP Report 350. The American Association of State Highway and Transportation Officials (AASHTO) recognizes multiple flexible, semi-rigid, and rigid systems which have been developed, tested and installed with the intention to contain and redirect vehicles “with masses up to 4,400 lb.” The Roadside Design Guide lists four barriers in the flexible systems category, six in the semi-rigid system category,

and six in the rigid systems category. Each system has been tested and approved and are currently being used on highways. The most commonly used roadside guardrails include the following:

### **Flexible Guardrails**

W-beam (Weak Post): The W-beam (weak post) utilizes a W-beam rail instead of steel cables as shown in Figure 2.4. The W-beam continues to be effective after minor hits “due to the rigidity of the W-beam rail element” (AASHTO, 2011).



Figure 2.4: Weak Post W-Beam Guardrail

Source: Elderlee, Inc., 2017

Ironwood Aesthetic Guardrail: This guardrail type consists of steel posts and steel-backed timber (AASHTO, 2011) as shown in Figure 2.5. The Ironwood guardrail is used for aesthetic purposes along scenic highways to blend with the natural surroundings.



Figure 2.5: Ironwood Aesthetic Guardrail

Source: Landscape Online, 2017

### **Semi-Rigid Guardrails**

Box Beam (Weak Post): This guardrail type consists of a box beam rail on weak posts as shown in Figure 2.6. The impact resistance results from the flexure and tensile stiffness of the rail. The posts are designed to break or tear away at the point of impact (AASHTO, 2011).



Figure 2.6: Box Beam (Weak Post) Guardrail

Source: AASHTO, 2005

Blocked-Out W-Beam (Strong Post): The most commonly utilized guardrail in use today. The system consists of steel or wood posts supporting a W-beam rail element that is blocked out with routed timber, steel, or recycled plastic spacer blocks as shown in Figure 2.7. The resulting resistance on impact is produced “from a combination of tensile and flexural stiffness of the rail and the bending or shearing resistance of the posts” (AASHTO, 2011). Strong post barrier systems do not require immediate repair upon receiving a moderate to low speed impact.



Figure 2.7: Blocked-Out W-Beam (Strong Post) Guardrail

Source: Corral Sales Co., 2014



Blocked-out Thrie-Beam: Consists of the same corrugated rail as previous systems but has three ridges instead of two, as shown in Figure 2.8.



Figure 2.8: Blocked-Out Thrie-Beam

Source: Elderlee, Inc., 2017

There are three types of the thrie-beam guardrails. These guardrails are briefly discussed in the following sections.

**Blocked-Out Thrie-Beam (Wood Strong Post) Guardrail:** A stronger version of the blocked-out W-beam guardrail. This results in less damage during low and moderate-speed vehicle impacts (AASHTO, 2011) and allows higher mounting of the rail which “increases the ability to contain vehicles larger than the standard passenger car under some impact conditions” (AASHTO, 2011).

The second system is the Blocked-Out Thrie-Beam (Steel Strong Post). This guardrail type originally used a steel block-out which failed to pass requirements provided in the NCHRP Report 350. The block-outs were replaced with routed timber or routed, recycled plastic. This system was able to contain and redirect a 20,000 lb. school bus but failed to keep the school bus upright (AASHTO, 2011).

The third guardrail type is the Modified Thrie-Beam Guardrail System. This system includes a deep steel block-out that has a triangular notch cut from its web as shown in Figure 2.9. The block’s design “allows the lower portion of the thrie-beam and the flange of the steel block-out to bend inward during a crash, keeping the face nearly vertical in the impact zone as the

posts are pushed backwards” (AASHTO, 2011). This design decreases the likelihood of a vehicle rolling over the barrier.



Figure 2.9: Triangular Notched Steel Block-Out

Source: AASHTO, 2005

Merritt Parkway Aesthetic Guardrail: This guardrail type is a semi-rigid guardrail that is used with the primary intention to enhance the safety of the highway users and also to provide an aesthetic aspect when placed along scenic highways as shown in Figure 2.10.



Figure 2.10: Merritt Parkway Aesthetic Guardrail

Source: Connecticut DOT, 2013

Steel-Backed Timber Guardrail: This guardrail type is a semi-rigid guardrail is used for the same reason as the Merritt Parkway Aesthetic Guardrail is used for. The system consists of wood rail backed with a thick steel plate and supported by timber posts as shown in Figure 2.11.



Figure 2.11: Steel-Backed Timber Guardrail

Source: The Paul Peterson Company, 2011

### **Rigid Guardrail**

New Jersey Concrete Safety shape, F-Shape Barrier, Vertical Concrete Barrier, Single Slope Barrier, Ontario Tall all Median Barrier and the Stone Masonry Wall or Precast Masonry Wall are currently in use. Each of these guardrails is either made of concrete or masonry with varying shapes and heights. Rigid guardrails have had satisfactory outcomes when tested with pickup trucks and single unit trucks. Most of these systems have been utilized as median barriers. Barrier height designs have been proposed to redirect heavier vehicles than passenger cars (AASHTO, 2011). Median barriers with higher walls have been effective in counteracting the overturning moment of trucks.

## **2.7 ROADSIDE SAFETY**

According to the Federal Highway Administration (FHWA), asset management programs vary among agencies. This results from the agencies available resources, their responsibilities and AM objectives. Most agencies throughout the United States allocate their funding, maintenance, and repair towards roadway pavement and bridges. There is more historical data to support funding and maintenance practices for pavement and bridges because pavement and bridge AM programs have been in effect for the past 10 to 15 years. These existing programs have been providing information that has been used for service life and “what-if” analyses. This information is utilized by the DOTs to make justified decisions at the strategic, network and

project levels. The decisions are focused on optimizing the allocation of resources for the management, operation, maintenance, and preservation of the infrastructure (FHWA, 1999).

Pavement management systems are the oldest and include many types of management systems due to pavements accounting for 60% of the total infrastructure assets that are managed by transportation agencies (Haas et al. 1994). FHWA estimated that the U.S. transportation infrastructure is valued at more than \$1 trillion, therefore it is imperative that funding allocation is effectively and efficiently managed due to limited budgets for transportation assets. Although pavement and bridges are a high-cost asset and account for most of the inventory, the safety and highway efficiency also depends on the performance of roadway safety assets (FHWA, 2005), which include signs, signals, lighting, guardrail, and pavement markings.

Highway safety design elements were first implemented in the late 1940s through the 1950s. “Horizontal alignment, vertical alignment, hydraulic design, and sight distance” are the most common roadside design hazards to utilize safety design elements (AASHTO, 2011). The focus of roadside safety design aspect began until the late 1960s. It was not until the 1970s that roadside safety design standards were required to be incorporated into highway projects. Highways that were designed and constructed before the 1970s would have to be considered for reconstruction due to the implementation of new safety designs that were not enforced at the time of design.

The primary purpose of roadside safety elements is “to protect motorists from potentially serious hazards located near the travelway” (Sicking, 2009). These hazards can include any of the following: “oncoming traffic, pavement edges, drop-offs, overpasses, sharp turns, solid objects close to the roadside like buildings or bridge columns, and other potentially hazardous objects” (Archambault, et al., 2007).

Guardrails were one of the many roadside safety elements implemented in the design of highway and roadway projects. Guardrails were implemented for their designed ability to absorb and redirect energy that is created during collisions. This function serves as a way to move the

passengers and the vehicles involved in the collision, away from the hazardous objects located behind the guardrail. The following discusses guardrail standards.

In 2009, the lowest number of deaths since the 1950s was recorded to be 33,808 people (AASHTO, 2011). During 1950-2009, the number of vehicle-miles traveled each year increased from 0.5 billion to 3.0 billion, approximately six and one-half times in a span of 59 years. During this period, the traffic fatality rate per 100 million vehicle-miles traveled had decreased from 7.38 to 1.13, approximately an 85% decrease. Improvements in roadway geometric design and roadside barrier performance have contributed to the reduction of the motor vehicle fatality rate (AASHTO, 2011).

## **2.8 GUARDRAIL ASSET MANAGEMENT**

Currently, guardrails must meet the evaluation criteria provided in the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) or the NCHRP Report 350 for each crash test, and the guardrail must also be evaluated and “found acceptable as a result of an in-service performance evaluation” (AASHTO, 2011). Guardrails that were installed before the acceptance of MASH, may remain in place, manufactured and installed as long as the criteria in the NCHRP Report 350 is met. It is recommended that existing guardrail that does comply with NCHRP Report 350 or the MASH to be upgraded when new reconstruction projects, resurfacing, restoration, or rehabilitation takes place. Guardrails should also be upgraded when severely damaged and in need of complete repair. There are six standard crash test levels presented in MASH and NCHRP Report 350 for guardrails. Each of these levels were established for the purpose of evaluating “occupant risk, structural integrity of the barrier, and post-impact behavior of the vehicle for a variety of vehicle masses at varying speeds and angles of impact” (AASHTO, 2011). Guardrail recommendations state that traffic guardrails must be installed if it decreases the severity of possible crashes. It is also possible that the placement of guardrails can lead to higher incident rates due to the location of the guardrail on the travel way. Subjective analysis and a benefit-cost analysis can also be

used to determine the feasibility of guardrail placement at the location of interest. The following are common transportation asset management information system (TAMIS) components:

1. Asset inventory;
2. Asset condition, performance, and utilization tracking;
3. Asset condition and performance prediction;
4. Treatment selection;
5. Resource allocation; and
6. Work planning and tracking support (AASHTO, 2013).

It is important for agencies to have an inventory because collected information can be used in models to forecast parameters that can be used to develop an evaluation process necessary for assets. Although it is the “building blocks” for any asset management system, many agencies have struggled to collect, store, and analyze inventory data for non-pavement and non-bridge assets. The following guidance, shown in Figure 2.12, provided in the “Transportation Asset Management Guide,” provides the data, functional components and the expected output within a Transportation Asset Management Information System (TAMIS).

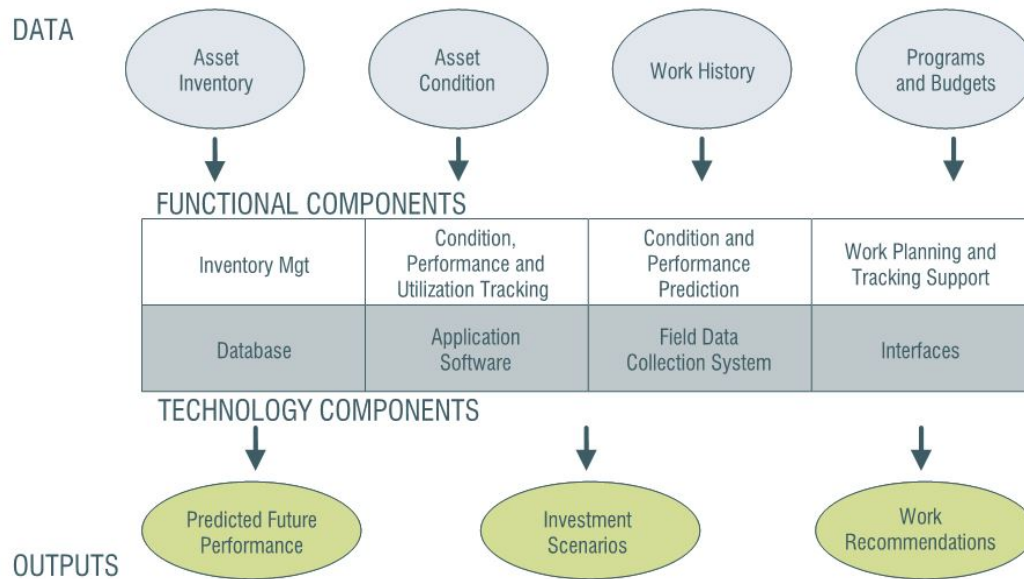


Figure 2.12: Data, Functional, and Technology Components of a TAMIS

Source: AASHTO, 2013

The following is a summary, provided in the American Association of State Highway and Transportation Officials (AASHTO, 2006), of data elements that are relevant for guardrails and should be collected and inventoried.

Inventory Attributes

- Guardrail length – Length of guardrail in feet
- Guardrail Side – Location of the guardrail whether it is on the left, right, or on both sides of the roadway.
- Guardrail type – Type of guardrail and category.
- Blockout Type – Type of blockout.
- Guardrail Material – Type of guardrail material.
- Construction year of Guardrail – The year of guardrail installation.
- Guardrail Height (Low/High > 3 in.)
- Guardrail Damage (percent of length)
- Guardrail Post Damage (Percent of posts)

The guardrail height is important because this is used to determine if the guardrail needs to be replaced. The height dependent replacement depends on whether the height meets the specifications mentioned in MASH and NCHRP 350. The guardrail damage is recorded for the purpose of assessing dents which cause a decrease in the structural capabilities of a guardrail. Also contributing to guardrail damage is rusting and corrosion of guardrail material of posts, fasteners, and blockouts.

### **2.8.1 Data and Inventory Collection**

It is recommended to include inspection and maintenance in guardrail review activities during the planning and design process for highway reconstruction or during highway repairs. It is also recommended to schedule routine inspections of guardrails within an agency. The data are most often collected manually or through mobile data collection. Manual data collection involves two or more data collectors and a vehicle capable of measuring the distances between the guardrails. A paper or digital log system is used to record the condition of the inventoried asset. The digital log requires a computer that is equipped with Global Positioning System (GPS). The mobile data collection process “involves the use of a vehicle equipped with a distance measuring device and/or GPS capabilities; digital video cameras; and the appropriate computer hardware to capture, store, and process the data collected” (AASHTO, 2006).

Not all DOTs have developed fully integrated systems to help manage their roadway safety assets. A 2005 FHWA document titled “Why Your Agency Should Consider Asset Management Systems for Roadway Safety” presents an overview of asset management systems that are used in New Mexico, Virginia, Florida, and Tennessee.

The asset management system used for tracking and recording guardrail inventory in the New Mexico Department of Transportation (NMDOT) incorporates a “virtual drive” feature through its Road Features Inventory (RFI). The RFI holds more than five million images and database information for each of the roadway asset photographed. In total, NMDOT inventories 31 types of roadway features. The data recorded includes “description and condition, the material



the asset is made of, the location of the asset (by latitude and longitude, roadway start and end mile marker, and roadway start and end mile point), the elevation of the location of the asset, and the asset's physical dimensions" (FHWA, 2005). Figure 2.13 shows a screen capture of the asset management system used by NMDOT.

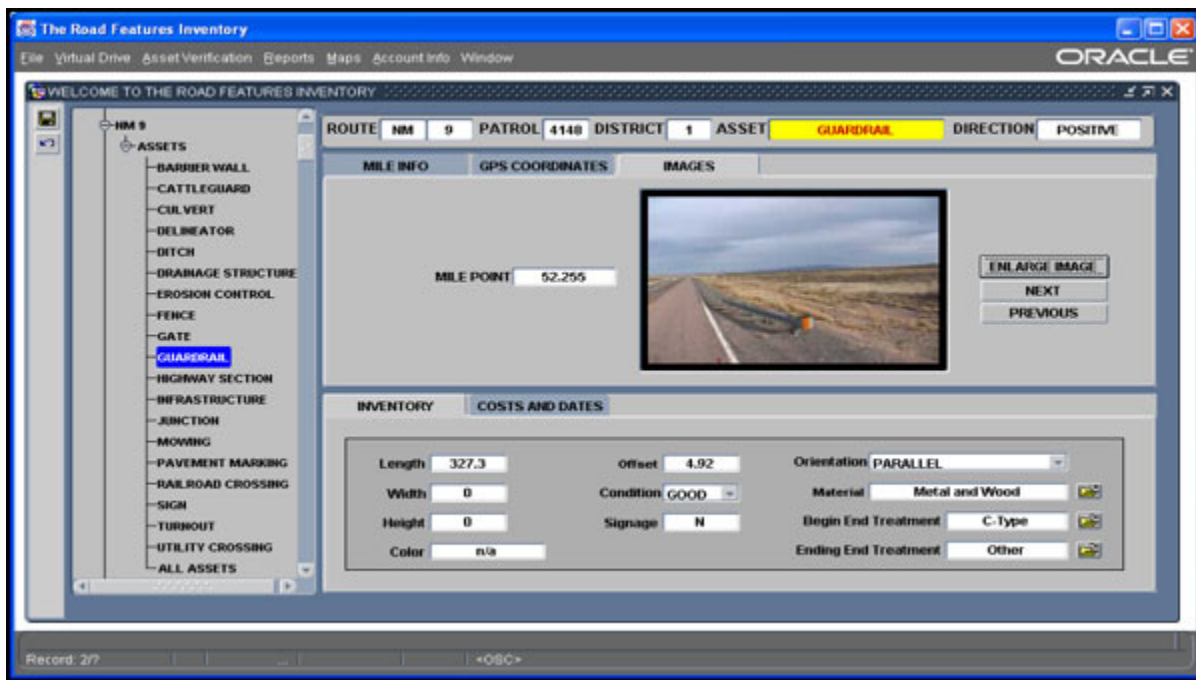


Figure 2.13: Screen capture from the NM RFI database for Guardrails

Source: FHWA, 2005

The RFI is incorporated with the Highway Maintenance Management System (HMMS) which is an interactive planning, budgeting, and reporting tool that is used to help make decisions.

Virginia utilizes a Random Condition Assessment (RCA) Data Collection which uses statistically based random sampling methodology to take inventory of various roadside assets including guardrails. The RCA module has the capabilities of providing information such as rail and post damage (extent of damage or deterioration to the asset) and whether the guardrail system meets the federal safety standards (VDOT, 2006).

Florida Department of Transportation (FDOT) uses a Roadway Characteristic Inventory (RCI) to store information about the State's roadway infrastructure. The RCI has more than one

million records that are accessible through an access-controlled Internet interface. A broad range of highway assets including guardrails along with 29 asset features such as roadway, location, and size are recorded into the RCI system. This system is used by “maintenance managers statewide as a tool for long-term planning and budgeting, for performance-based management, and for district-office decisions on resource allocation” (FHWA, 2005). The RCI data collection is then transferred into an annual workload that is then converted into the Maintenance Rating Program (MRP) performance standard. It is through these systems that FDOT can determine the workload required to maintain their guardrails to their required or set performance standards. A statistical sampling technique is used by the FDOT MRP that allows FDOT districts to collect random condition assessment data every four months.

The Tennessee Road Information Management System (TRIMS) is a data collection tool that includes public road information. The categories that are collected include signs, guardrails, and pavement markings. TRIMS is a planning tool that is supported by TDOT’s planning division that functions as a maintenance management system.

The typical inventory for guardrails is 5-10 years while the inspection cycle is ongoing (AASHTO, 2006). The frequency in which the inventory collection is executed depends on the level of detail needed for the data collection. Guardrails that are readily accessible and highly used as a safety asset are more frequently inventoried. A W-Beam guardrail should be inspected and inventoried on an annual or biannual basis as suggested by the W-Beam Guardrail Repair Guide (Fitzgerald, 2008).

Guardrail inventory in conjunction with geographic information system (GIS) has been made possible by Esri®, a geographic information system company. Esri® produces ArcGIS which is a mapping and spatial analytical software used to capture, store, and analyze data across multiple databases. (ESRI, 2017). ArcGIS for Local Government, developed by ESRI, focuses on providing a platform for local governments to store their geographic information to “Maintain right of way assets; meet transportation and environmental quality needs; coordinate and plan capital projects; and operate parks, and government facilities in a safe and effective

way.” (ArcGIS, 2017). The Guardrail Inventory software, provided by ArcGIS for Local Government, is utilized by public works field staff to build a comprehensive inventory of guardrails. The first Guardrail Inventory was made available in December 2014 and has included updates through January 2017. Agencies use this along with ArcPad which provides the ability for personnel to record data easily out in the field.

### **2.8.2 Guardrail System Performance Measures**

Currently, Florida DOT and Iowa DOT follow a pass-fail asset rating approach, while North Carolina DOT follows an LOS asset rating approach, and Utah follows a hybrid asset rating approach which is a combination of the pass-fail rating and LOS rating.

Florida Department of Transportation (FDOT, 2015) has a Maintenance Quality Assurance condition (MQA) assessment approach that provides the desired numerical maintenance conditions used under their Maintenance Rating Program (MRP). FDOT recognizes 11 specifications used to determine if the guardrail sections meet the MRP standards. The specifications used include the percentage of guardrail length that has twisted guardrail blocks, whether or not the W-beam rail has been penetrated, whether the W-beam rail is lapped incorrectly, or whether 25 feet of the continuous guardrail is 3 inches above or 1 inch below the desired height, to name a few.

Utah Department of Transportation (UDOT) uses a grade scale based on the percentage of deficient length. The grade scale is shown in Table 2.2. The grade is determined by calculating the percent of guardrail deficient length to total guardrail length.

Table 2.2: UDOT Guardrail System Condition 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+	46.79-100.00	F-
23.42-26.81	C		

Source: UDOT, 2012

If the guardrail has 0-10.02 % deficient length, then the guardrail falls into the “A” grade range with 90-100% of features in acceptable condition. If the guardrail has 10.03-20.01% deficient length then the guardrail falls into the “B” grade range with 80-90% of features in an acceptable condition. The other grades are broken into percent deficient ranges. The grading scale is also used as a target scale by UDOT’s Quality Improvement Team (QIT) for Maintenance Management Quality Assurance Plus (MMQA+) grades in 2013. The MMQA+ program has different uses in the statewide, station level, and region or area level.

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

1. To communicate how well UDOT is preserving their infrastructure.
2. As a budgeting tool.
3. To determine where more resources could be valuable or where resources can be reduced.
4. To help establish goals for future levels of maintenance with consideration of available budget and resources.

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

1. 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.

2. To compare budgets to current asset conditions and request that funding be moved from one activity to another to best meet MMQA+ targets.

### **2.8.3 Guardrail Service Life**

Through MAP-21, initiated in 2012, all states are required to create and follow a Transportation Asset Management Plan (TAMP). As of today, 40 plus states have or are developing asset management systems. Through this literature review, it is concluded that there are varying asset management plans at different maturity levels that have been developed within the past five years.

Many asset management plans for highway assets are at the beginning stages of development or in the testing phase. It is for this reason that limited inventory and other information for highway assets such as guardrail is limited. This has been a challenge through the development of this thesis. One piece of information that is currently not reported is the guardrail service life for different types of guardrails for each state. Seattle DOT's Status and Condition report states that guardrails "are not regularly inspected and are maintained on a customer request basis" (SDOT, 2008). SDOT uses guardrail age to determine a replacement cycle. The replacement life cycle follows the following criteria: newly installed guardrail has an expected life of 25 years, guardrail degrades to fair condition in 17 years, the guardrail is considered in poor condition and eligible for replacement at the end of its useful life. A more recent edition of the SDOT Status and Condition report states that guardrail has a useful life of 20 years (SDOT, 2015). W-Beam guardrails may last 10 to 20 years if there are no vehicle crash accidents. Other types of guardrails have longer lives and may last thirty years or more if they do not receive any major damage. Agencies need to adjust the guardrail deterioration condition rate to local conditions and maintenance practices.

Many safety assets lack life-cycle costs because maintenance costs are budgeted for within a general budget. In many guardrail asset management practices, emergency repairs and guardrail replacement is incident driven (SDOT, 2015). This type of asset management practice

follows a reactive approach instead of a proactive approach which does not necessarily require life-cycle costs and documentation of guardrail service life.

A straight line deterioration rate is not considered in the model. In order to confidently use a straight line deterioration rate, consistent long-term guardrail age information would have had to have been analyzed to better incorporate a straight line deterioration rate in the model. A transition matrix was used in order to use the guardrail condition data that was available. The matrix development is discussed in Section 4.3: Guardrail Transition Matrix.

#### **2.8.4 Guardrail Deterioration and Damage**

Utah Department of Transportation (UDOT) guardrail maintenance decisions are based on the guardrails condition. For example, UDOT has regression curves based on performance versus the annual cost to maintain the guardrail and are used to formulate the budget needed to improve or maintain the guardrail performance (UDOT, 2012).

To quantify deterioration, UDOT uses the deterioration rates, listed in Table 2.3. The deterioration of 2.5 years assumes that the guardrail is not involved in any vehicle accidents. After 2.5 years, the guardrail current condition grade deteriorates by one condition grade. With many variables attributed to guardrail deterioration, the deterioration rate to move from one condition category to another can vary depending on the guardrail material and guardrail location. In general, guardrails deteriorate over time due to the environment elements that surround the location of the asset. Through time the rail, end-terminal treatment, and the support post material influence the deterioration rate of the guardrail as well.

Table 2.3: Guardrail Deterioration Condition Rate

<b>Deterioration in Condition Rating</b>	<b>Time After Installation (Years)</b>
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.

Maintenance and repair typically occur when a guardrail is damaged following an accident, vandalism, or deterioration. It is recommended to leave the guardrail as is if the guardrail meets the original standard and is in good and sound condition. If the guardrail is damaged or has deteriorated more than 50% of the entire length, then it should be repaired or replaced (FDOT, 2015). If an agency has developed an asset management system, then a risk assessment is recommended. “It is important that each agency develop guidance for when to make repair” (Fitzgerald, 2008). The W-Beam Guardrail Repair Guide provides photographs showing examples of damaged guardrails and their respective damage category corresponding to Table 2.4. The photographs are shown below.



Figure 2.14: Guardrail Damage

Source: FHWA, 2008



Figure 2.15: Guardrail Damage.

Source: FHWA, 2008



Figure 2.16: Guardrail Damage

Source: FHWA, 2008

The W-Beam Guardrail Repair Guide also provides examples of end treatment and transition damages. Based on the damage to the guardrail, Table 2.4 can be used to categorize the functionality of the guardrail.

Table 2.4: Guardrail Damage Classification Details

Damage Category	Damage Attributes
(1) Non-Functional	Rail element is no longer continuous 3 or more posts broken off no longer attached to rail Deflection of rail element more than 18 in. Rail element torn Top of rail less than 24 in.
(2) Damaged but should function adequately under majority of impacts	Rail element is continuous (can be bent or crushed significantly) 2 or fewer posts are broken or separated from rail element Deflection of the rail element is less than 12 in.
(3) Damaged but should not impair the guardrail's ability to perform	Rail element is continuous (can be crushed or flattened) No posts are broken off or separated from the rail element Deflection of the rail element is less than 6 in.

Source: FHWA, 2008

The W-Beam Guardrail Repair Guide from FHWA is a comprehensive guide on the types of damage requiring repair, but minimal guidance is provided in terms of quantitative guidelines corresponding to the types of damage. A few examples include the following:



Alabama DOT (ADOT) – Criteria Description: Repair or replacement of guardrail sections, posts and hardware due to crash damage or normal deterioration. ADOT has a non-quantitative maintenance manual for guardrail repair (NCHRP, 2012).

South Carolina (SCDOT) – Criteria Description: Threshold condition: “Guardrail damaged or not functioning as design.” SCDOT has non-quantitative maintenance assessment criteria for guardrail repair (NCHRP, 2012).

Currently, condition states and performance targets set for guardrails include the following (AASHTO, 2006):

- a. Good: Structurally sound due to the presence of all components and meeting current state and federal specifications.
- b. Repair: Missing component parts.
- c. Replace/Upgrade: Do not meet current design specifications and have been structurally damaged by accidents or deterioration.

Although there are many guidelines to classify the guardrail damage there is a lack of models presenting key information such as the life-cycle of the guardrail, deterioration, and condition. The absence of these models decreases the ability to accurately determine condition, deterioration and life-cycle fluctuations between agencies. Condition based models available to agencies can help determine if the recorded data are adequate and to determine if the guardrail asset management program is achieving their goal in lengthening the life-cycle.

### **2.8.5 Guardrail Preservation Policies**

Guardrail preservation policies are usually formulated by a central office that provides policies for maintenance, specifications for materials, and criteria to allocate funding. The Guardrail Replacement and Maintenance Guidelines developed by the Minnesota Department of Transportation (Marti, 2010) states the following, “Local jurisdictions continue to perform guardrail maintenance but there are no current guidelines to ensure that maintenance practices are to standard and are consistent throughout the state.” MNDOT inspection and maintenance

practices include repairing guardrail sections that have been damaged and have become a hazardous object to the motorists. It is recommended for agencies to consider the documentation process for the installation and repairs for each type of system and the process to include “response time requirements for repairs and required spare parts inventory.” Identifying who makes decisions on reusing parts and who inspects repairs can not only help agencies provide public safety but also as a way to protect the agency against possible lawsuits (Marti, 2010).

The Design, Construction and Maintenance of Highway Safety Features and Appurtenances provide helpful information as guidance on inspection and maintenance practices developed by each agency. It is imperative that periodic, consistent inspection and maintenance are performed to ensure that the roadside guardrail performs its intended safety function. Review and inspection should be considered in the planning and design process for highway reconstruction and repair. Inspections not only occur for scheduled periodic inspections but also by crash reports that are submitted to the agency.

DOTs use varying routine and corrective maintenance procedures and guidance based on the available funding, staff and equipment that can be allocated by the agency. Fitzgerald (2008) recommends that maintenance practices should be conducted annually or biannually. Different combinations of maintenance activities are applied to guardrails depending on the damage and available resources. Marti (2010) provides routine maintenance and crash (replacement) related maintenance guidelines that are applied to W-beam guardrails. Routine maintenance requirements are minimal. Occasionally, it may be necessary to replace bolts or realign posts damaged by snowplowing. Some agencies routinely apply herbicides along roadside barriers to avoid difficulties involved in mowing grass and weeds along and under the barrier. This pesticide might cause wood deterioration to occur. Modifications to the barrier must not be made unless consistent with the most recent standard for the barrier type. Barrier components or features must not be omitted (Marti, 2010). The following are general guidelines for W-beam guardrail routine maintenance and crash (replacement) related preservation activities:

1. Standard specifications for the barrier in question should be reviewed to ensure that proper details are followed.
2. All guardrail parts must meet appropriate specifications. If used or salvaged parts are used, they must be in good condition.
3. 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.
4. During repairs, roadside conditions affecting performance should be checked, such as the introduction of new fixed objects.
5. If significant damage occurs to a substandard barrier or terminal, it should be upgraded to current standards.
6. Feedback on recurring problems should be provided to design and construction staff so future installations can be improved (Marti, 2010).

Crash related maintenance guidelines, specifically, for W-beam rails are also included. Replacement of the W-beam is necessary when one or more sections are torn or severely deformed. Crash related maintenance and repairs include replacement and realignment of the posts, blockouts, and damaged W-beam guardrail (Marti, 2010). SCDOT uses the following to classify guardrail damage:

**Severe** – Guardrail or end treatment damage is so severe that it no longer functions as designed or has become a hazard to the traveling public (SCDOT, 2010). Examples of severe damage include situations when the W-beam rail has been completely pulled apart, when there are at least three or more consecutive posts that have broken off and are no longer attached to the W-beam rail, when there are at least three or more consecutive posts that have rotten due to natural weathering or herbicide, and when the rail is 12 inches or more out of alignment. For severe guardrail damage, the repair should be made on the fourth day after notification.

**Moderate** – Guardrail or end treatment is apparently damaged but will still perform as designed for most traffic conditions (SCDOT, 2010). Examples of moderate damage include situations when the rail is badly bent or crushed but not completely separated from any part of the

guardrail, when there are no more than two consecutive posts that have been broken or separated from the rail, when the rail pushed out of alignment less than 12 inches, or when the guardrail does not meet the height requirements. For moderate guardrail, damage repairs should be conducted no later than ninety days from the date of discovery.

**Minor** – Guardrail or end treatment damage is minor and though not aesthetically pleasing, it will still perform its intended function (SCDOT, 2010). An example of minor damage includes dings along the length of the guardrail. For minor guardrail damage, repairs should be performed until convenient to the work schedule, and all severe and moderate repairs have been completed.

As another example, WSDOT's guardrail asset management strategy was dependent on their Pavement Preservation Program which does not consistently align with the operational life of a guardrail. This can cause for guardrail to be left in place past their effective life or be replaced before the end of their operational life resulting either in an increase in user safety risk or a premature cost. WSDOT established funding programs to justify how to “optimize the use of limited budget resources and maximize the life cycles of signs, guardrail, guardrail terminals and transitions, roadside barriers, and bridge rails” (WSDOT, 2012).

## **2.9 SUMMARY**

Agencies are required to follow criteria in determining priority among the assets. As pointed out in the literature review, a handful of DOTs are gathering inventory for many of their assets, and as their inventory grows, there is a need to use the data to develop helpful guides and policies that can be integrated into their AM programs.

AM, AM federal programs, principles, performance measures, and preservation policies were previously discussed in a general asset management context followed by guardrail standards, roadside safety, and guardrail AM. Through the literature review it can be concluded that guardrail AM is relatively new. Therefore, the development of guardrail support tools can provide agencies additional support to enhance their guardrail AM objectives and utilize their

inventory to forecast parameters to justify guardrail AM practices, resource and funding allocation.

The absence of a guardrail support tool poses a challenge for highway agencies because without a condition based support tool to support the development of a preservation program, there are no standard practices followed to provide strategies and guidelines to maintain and lengthen the life-cycle.

Chapter 3 describes the development of the Guardrail Asset Management Framework.

## **Chapter 3: Guardrail Asset Management Framework**

### **3.1 BACKGROUND**

Asset management (AM) involves engineering and economic principles to support decision-making within a hierarchy of decision-making levels. The three core asset management levels are project level, network level, and strategic level (FHWA, 2006). The asset management levels provide a platform to optimize the allocation of resources for management, operation, maintenance, and preservation of the transportation infrastructure (FHWA, 1999). The following defines each of the three core asset management levels.

The first core asset management level is the project level. Project level focuses on decisions concerning project designs. Project level is also referred to as “field level” or “operational level” due to its involvement with how the actual work is going to be done (FHWA, 2006). This asset management level oversees the overall work plan and determines which projects will support the agencies’ goal in achieving their performance measures.

The next level in the hierarchy of asset management levels is the network level. Network level focuses on decisions relating to the maintenance, rehabilitation, and construction strategies with budget allocation and planning being at the forefront of their decisions. Network level determines funding and treatment needs, forecasts future conditions, prioritizes assets requiring treatments, and also considers deferred treatment information. All of this information guides the network level to make budget allocation decisions.

At the top of the asset management level hierarchy, is strategic level. The strategic level focuses on decisions concerning broader asset management issues involving maintenance, rehabilitation, and construction strategies. This asset management level “pertains to strategic decisions concerning all types of assets and systems within the civil engineering environment” (FHWA, 2006) along with budget allocation and planning at the forefront of asset management decision-making.

It is easily understood that each asset management level plays a major role in an asset management program. Therefore it is imperative that each of the asset management levels be

present and that their scopes are clearly defined to achieve effective and efficient decision-making (FHWA, 2006). The network level scope was adhered to for the Guardrail Asset Management Framework.

As shown in Figure 3.1, network level is in the mid-range of the asset management level hierarchy. Network level requires a reasonable amount of data with a reasonable amount of detail as compared to strategic level. Network level involves less detailed data as compared to project level involves more detailed data. Also, the level of decision-making made by the asset management levels increases from project level to strategic level, meaning the network level is at the mid-point of the decision-making level.

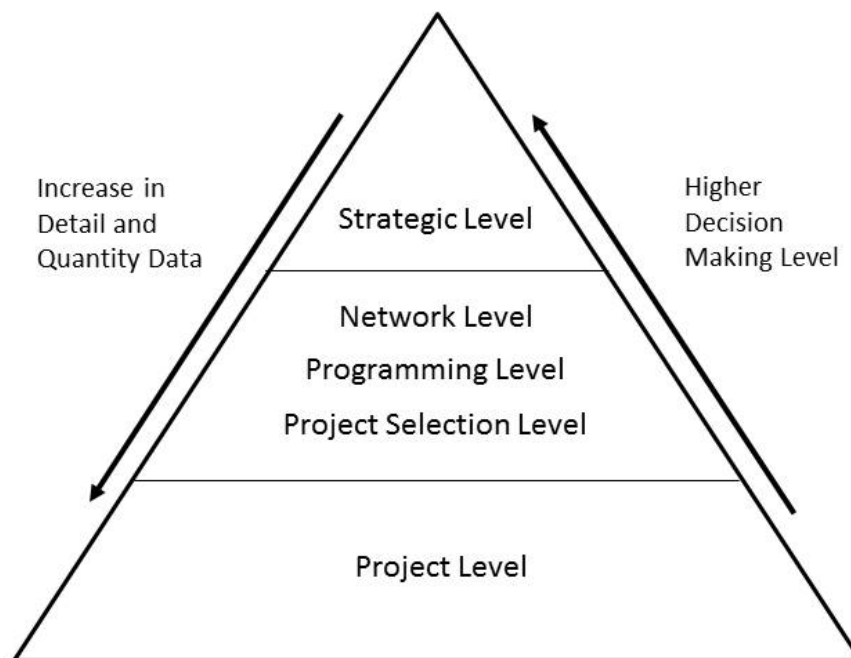


Figure 3.1: Relation between Decision-Making Levels

Source: FHWA, 2006

The existing performance measures and asset management programs have set the foundation for developing the guardrail network framework and the model. The literature review focused on the availability of guardrail resources that are used by agencies to determine the

functionality, maintenance, rehabilitation, and replacement of a guardrail. The following sections describe the guardrail framework that incorporates literature review findings.

### **3.2 FRAMEWORK DESCRIPTION**

The Guardrail Asset Management Framework shows the process to be considered as part of the asset management program for guardrails. The framework ensures that the collected data will be utilized in the model, described in Chapter 4, which is the minimal data collected by agencies. Through a comprehensive literature review, it was determined that many agencies collect data without predefining the data's use. Data used for the model were very limited therefore the framework lists the necessary information needed for the model, as well as additional data that should be collected to improve the model's accuracy. The Guardrail Asset Management Framework is shown in Figure 3.2.



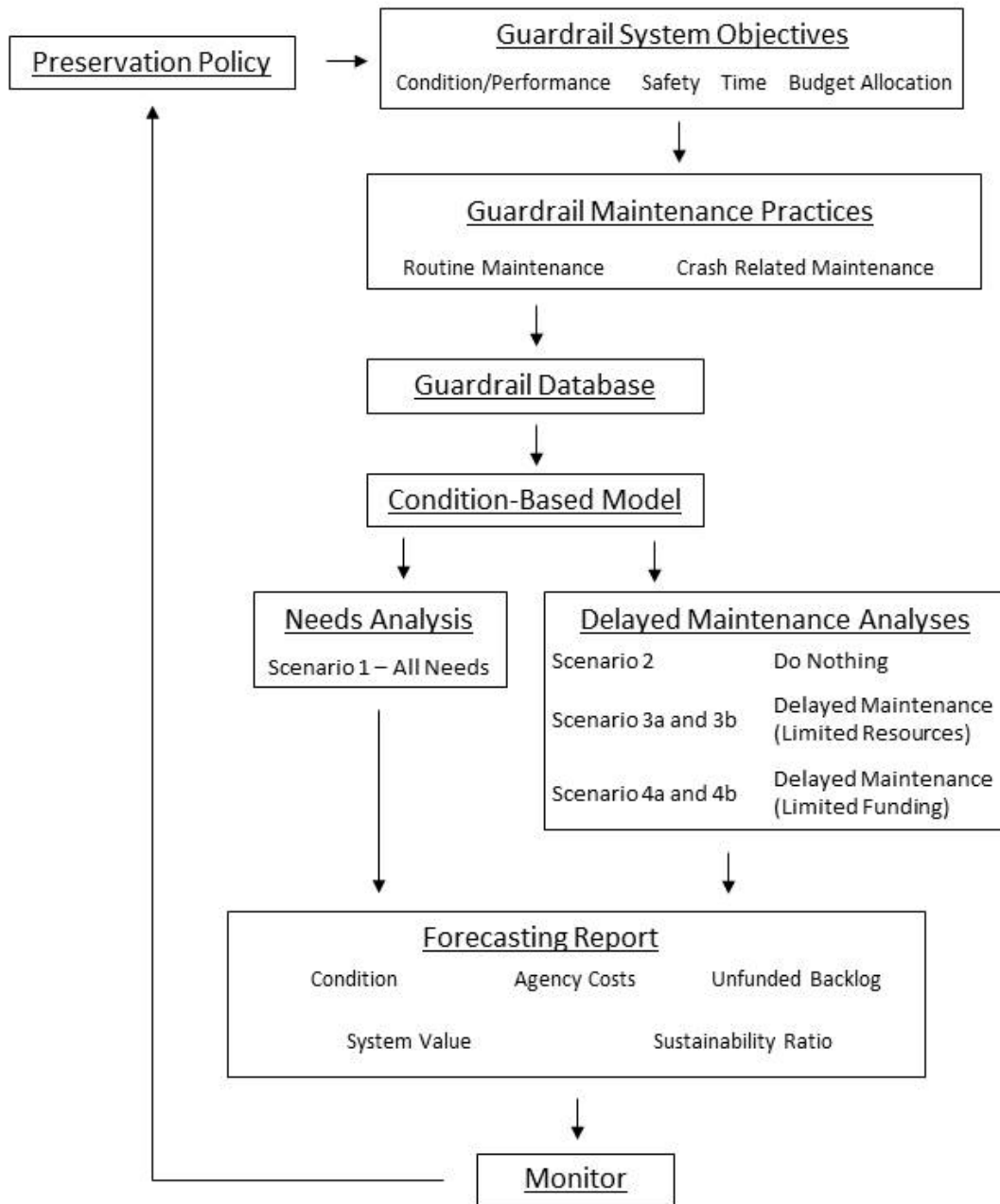


Figure 3.2: Guardrail Asset Management Framework

The following will define each of the steps provided in the framework.

### 3.3 OBJECTIVE

The agency needs to have a goal highlighted through a primary objective and secondary objective. It is imperative that the agency determines what they want to achieve, how they want

to achieve it, and a time frame that the goals are expected to be achieved in. This not only ensures that responsibilities are clearly defined for each group within the agency but also ensures that progress is being made and achieved.

Guardrail condition and performance, associated safety, time, and budget allocation are objectives that are to be considered in the Guardrail Asset Management Framework.

The condition and target performance objectives that were adopted for the framework and model is the Level of Service (LOS) rating utilized by Utah DOT (UDOT), North Carolina DOT (NCDOT), South Carolina DOT (SCFOT), Texas DOT (TXDOT), and Washington State DOT (WDOT) (NCHRP, 2012). The desired condition is undamaged guardrail elements such as the guardrail, posts, offset blocks, and connection hardware. All of these elements are to be accounted for within each system to ensure that the guardrail performs as it is intended to.

Incorporating Safety, within the Guardrail Objective, is significantly affected by the decisions made and achieved for the condition and performance of the guardrail network. The agencies' decision to achieve a certain condition within the entire guardrail system means that there is a level of risk willing to be accepted. Accepting that the guardrails will not all be categorized as Condition A or Condition B, throughout the entire year, can mean that some guardrails will not be receiving maintenance to achieve a better condition grade or maintain its current condition. This affects the performance of the guardrail system when it is impacted by a vehicle. The condition of the guardrail during impact may be attributed to the severity of the crash. The correlation between the safety and condition is not incorporated into the framework or the model, presented in Chapter 5 but is one that should be considered for future research.

As is considered in many business plans, "time is money," and this is exactly the case for an asset management program. The necessary resources such as funding, material, and laborers are all affected by the time that is available to achieve the objectives and vice versa. Time, in some cases, is affected by the available funding, material, and laborers available.

The previously discussed objectives tie into budget allocation directly. The amount of budget available yearly can directly influence the condition and performance to be met, as well

as the safety, and the time to achieve the agency goals. With the framework utilized over a period of time, decisions regarding the objectives can be effectively discussed by analyzing results from the model. This can significantly affect the yearly allocated budget and the ability to plan for budget allocation in short- or long-term planning.

At the beginning of the fiscal year, it is important to discuss and revise the objectives, and determine if they can all be incorporated into the guardrail asset management program. The following questions, listed in Table 3.1, are minimal and have been considered within the Guardrail Objectives for the overall guardrail network.

Table 3.1: Guardrail Objectives - Questions

<b>Condition/Performance</b>	<b>Safety</b>	<b>Time</b>	<b>Budget Allocation</b>
Does the agency want to achieve 80% of their entire guardrail network to be in Condition B, or C?	How does this impact the safety of motorists? Is there an increase in accident severity?	In what time-frame should this condition be achieved? 1 year, 3 years, or 5 years?	How much funding is necessary to achieve this condition within the set time frame?
Does the agency want to achieve a Condition of B while currently the Condition is D?	How does this impact the safety of motorists? Is there an increase in accident severity?	In what time-frame should this condition be achieved? 1 year, 3 years, or 5 years?	How much funding is necessary to achieve this condition within the set time frame?
Does the agency want to achieve a Condition of A?	How does this impact the safety of motorists? Is there an increase in accident severity?	In what time-frame should this condition be achieved? 1 year, 3 years, or 5 years?	How much funding is necessary to achieve this condition within the set time frame?

### 3.4 MAINTENANCE

As found in the literature review, guardrail preservation policies vary among DOTs and are affected by the available funding, staff, and equipment. The types of maintenance for the guardrail framework will focus on routine maintenance and crash related maintenance.

Routine maintenance will be conducted biannually if resources are available. The objective of routine maintenance is to verify that all guardrail sections within the guardrail are accounted for, and that all elements are positioned correctly so that the guardrail performs as it is

intended to. The guardrail routine maintenance includes replacing or tightening post attachment bolts and realigning posts, as well as applying herbicides along the roadside barriers.

Crash related maintenance will be conducted after crash notifications are received. The guardrail crash related maintenance is conducted for moderate and minor damaged guardrails. As noted in the Guardrail Replacement and Maintenance Guidelines (Marti, 2010), minor impacts along the length of the guardrail requires no maintenance response since most minor impacts result in cosmetic damage. Maintenance interventions are based on time and the specified condition for the guardrail. As noted in Florida DOT's maintenance manual (FDOT, 2015), guardrails are repaired or replaced when damage is more than 50% of the entire guardrail length. For moderate impacts, damage is centralized within one or two sections and also involves minor post misalignment (Marti, 2000). Moderate damage includes situations when the rail is severely bent or crushed but has not separated from the guardrail. Other moderate damage examples include situations when no more than two consecutive posts have been broken or separated from the rail, when the rail is pushed out of alignment less than 12 inches, or when the guardrail does not meet the height requirements (SCDOT, 2010).

### **3.5 INVENTORY**

If resources are limited then data collection should only be conducted during the bi-annual routine maintenance to ensure that key data are collected twice a year specifically at the beginning and at the end of the year. For data collection, key data should be collected. Key inventory includes the following:

1. Location
2. Guardrail Length
3. Guardrail Deficient Length
4. Guardrail Damage
5. Roadway classification; Major Arterial, Minor Arterial, Collector, Local Road
6. Location geometry, i.e., horizontal curves, vertical curves, embankments in the area
7. Traffic volume
8. Installation date

9. Accident reported information
  - a. Crash Location
  - b. Cost

Aside from collecting the data, it is imperative that an identification system is incorporated into the inventory. Incorporating an identification system also allows the agency to identify each guardrail and view the data collected within each of the consecutive years. This will ensure that the collected data can be easily tracked and be easily accessed and used. The inventory to be collected adheres to the practices already being followed by agencies and in most cases is data that agencies might have available to them.

### **3.6 CONDITION-BASED MODEL**

The Condition-Based Model is used to run 6 different scenarios that depict situation that may be experienced by agencies. These scenarios can also be used to forecast changes in their guardrail system. The following defines each of the scenarios related to the Needs Analysis and the Delayed Maintenance Analyses.

#### **3.6.1 Needs Analysis**

The needs analysis, defined in Table 3.2, is used to determine the maintenance funding required to preserve the guardrail system in acceptable conditions specified by the agency. The scenario runs in the model and identifies the needs of maintenance and replacement of deficient guardrails, and forecasts the guardrail condition, and other forecasting reports, discussed in Section 3.5, over a 10-year analysis period. The Needs Analysis is depicted by Scenario 1 listed in Table 3.2. Scenario 1 mirrors the best case scenario where the agency has no funding or maintenance constraints.

#### **3.6.2 Delayed Maintenance Analyses**

Five different scenarios were developed to perform delayed maintenance runs using the Condition-Based Model. These scenarios best mirror realistic situations to model “real life” scenarios that may arise in an agency’s asset management program.

Table 3.2 lists the scenarios included in the framework and used in the Condition-Based Model.

Table 3.2: Guardrail Needs and Delayed Maintenance Scenarios

Scenarios			Description
Needs Analysis	1	All Needs (Base-line)	Maintenance and replacement activities are performed with sufficient funds to implement the agency's preservation plan.
	2	Do-Nothing (No Maintenance Activities)	Maintenance and replacement activities are not performed within the 10-year analysis.
Delayed Maintenance Scenarios	3a	Delay Maintenance activities by 1 Year	Maintenance and replacement activities are delayed 1 year.
	3b	Delay Maintenance activities by 3 Years	Maintenance and replacement activities are delayed 3 years.
	4a	Delay Maintenance due to Limited Budget (80% Baseline)	Maintenance and replacement activities are delayed due to a limited budget.
	4b	Delay Maintenance due to Limited Budget (60% Baseline)	Maintenance and replacement activities are delayed due to a limited budget.

Scenario 2, known as the do-nothing model, was developed to model a scenario where the agency does not allocate any resources to the guardrail network for the entire analysis period.

Scenarios 3a and 3b model scenarios where the agency decides to or has to delay maintenance. The delayed maintenance may occur due to policy changes or limited resources. If a guardrail section requires maintenance in year<sub>n</sub> then the maintenance activity is postponed by 1 year in Scenario 3a and 3 years in Scenario 3b.

Scenarios 4a and 4b model scenarios where the agency decided to, or has to delay maintenance due to a limited budget.

It is recommended for agencies to use criteria that best fit their methods and conditions.

### 3.7 RESULTS

The Condition-Based Model provides forecasting reports for each of the scenario runs. The forecasting reports include guardrail condition, agency costs, unfunded backlog, guardrail system value, and the guardrail sustainability ratio. The results and forecasting reports can be used to monitor the guardrail network and to provide feedback to be incorporated into the

Guardrail Objectives for the following fiscal year. The results can also be used to assist agencies in the development or advancement of guardrail preservation policies. The following defines each of the forecasting reports.

1. Agency Costs: Maintenance and replacement cost resulting from the maintenance and replacement activities performed on the guardrail sections within the guardrail. This cost is representative of investments made to keep the guardrail functioning as intended.
2. Unfunded Backlog Costs: Costs representing the required funds necessary to carry out the maintenance and replacement activities but are either not performed due to maintenance delay or funding constraints.
3. Guardrail System Condition: The percentage of guardrails within the guardrail system in Condition A, B, C, D, and F.
4. The Guardrail System Value: Directly related to the overall condition of the guardrail system. The System Value results, calculated as the difference between total guardrail replacement costs (costs of replacing each guardrail within the system) and the funds needed to actually maintain and replace the guardrail sections within the guardrail that require maintenance and replacement activities, is also provided.
5. The Guardrail Sustainability Ratio: Illustrates the amount of allocated funds in comparison to the actual funds needed. The Guardrail Sustainability Ratio ranges from 0 to 1, where 0 corresponds to no funds available and a value of 1 corresponds to an agency having funds to cover all of the funds needed to maintain their asset.

The following chapter discusses the development of the guardrail Condition-Based Model.

## **Chapter 4: Guardrail Condition-Based Model for Preservation Policy Development**

Highway assets have different asset management procedures that have evolved at different rates resulting from resource availability and priorities within the transportation agency. The primary goal for highway agencies is safety on their roadways by reducing the rate of roadway fatalities (Performance, 2017). It is for this reason, and because of limited funding, that highway safety assets such as signs, signals, lighting, guardrails, and pavement markings are being considered and included in transportation asset management (AM) plans. Inventory for highway safety asset facilitates agencies with forecasting maintenance costs on the safety assets to make sure that it is performing as intended to. The Condition-Based Model focuses on utilizing inventory that has already been collected by agencies to formulate a guardrail preservation program. The model helps to develop a connection between the data that is being collected and the outcome that agencies expect from their guardrail system.

Current guardrail maintenance procedures and documentation were considered in the development of the Condition-Based Model. One of the primary goals is to develop a Condition-Based Model that can utilize project-level inventory to forecast critical parameters for strategic management decision-making. This will ensure that the network-level data can be used in the model.

### **4.1 DATA INPUT**

The key project-level inventory used in the guardrail preservation model includes total guardrail length, guardrail defective length, and average daily traffic (ADT). The total length of the guardrail and the guardrail defective length, which are recorded in feet, are needed to calculate the guardrail defective percentage. The guardrail defective percentage corresponds to a defective condition grade. The defective condition grade and the defective percentage are used to determine the maintenance activity to be performed on each guardrail that is in Condition A, B, C, D, or F. The inventory is used as the input data for the condition at the beginning of year one



of the 10-year analysis. The limited amount of data required for the model is attributed to the current data availability. Also, through the literature review, it was determined that limited project-network inventory is currently being collected by most transportation agencies. Complimentary data used in the guardrail preservation model includes maintenance cost and replacement costs.

#### 4.2 CONDITION-BASED MAINTENANCE ACTIVITIES

Maintenance activities are condition-based, therefore depending on the condition, a maintenance activity will be applied to the guardrail. Table 4.1 provides the defective condition grade with the corresponding deficient percentage, damage severity, condition based maintenance activities, and the cost of the maintenance activity per linear foot.

Table 4.1: Condition-Based Model - Maintenance Activity and Costs

<b>Defective Condition Grade</b>	<b>Percent Deficiency</b>	<b>Damage Severity</b>	<b>Maintenance Activity</b>	<b>Cost (\$/ft.)</b>
A	0-10	Very Minor	Do-nothing	\$0
B	10-20	Minor	100% Maintenance	\$7
C	20-30	Very Moderate	60% Maintenance, 40% Replacement	\$10.20
D	30-40	Moderate	20% Maintenance, 80% Replacement	\$13.40
F	> 40	Severe	100% Replacement	\$15

The cost of maintenance activities vary among DOTs, therefore, an average estimated cost to maintain a linear foot of guardrail is based on the United States Department of Agriculture (USDA). The percent deficiency, provided in Table 4.1, is also provided in Table 4.2. Table 4.2 was adapted from UDOT's Guardrail System Condition Grading Scale provided in Table 2.2.

Table 4.2: Percent Deficient Grade Scale

<b>Percent Deficient</b>	<b>Grade</b>
0.00-10.02	A
10.03-20.01	B
20.02-30.00	C
30.01-39.99	D
40.00-100.00	F

The following section defines each of the defective condition grades listed in Table 4.1.

The defective condition grade A means that the guardrail has 0-10% deficient length with 90% or more of guardrail length in good condition. Condition A corresponds to a guardrail that is structurally sound due to the presence of all guardrail components and meets current state and federal standards. Guardrail sections in Condition A require no maintenance.

Condition B means that the guardrail has 10-20% deficient length with 80% or more of guardrail length in good condition. Condition B corresponds to a guardrail that has missing bolts, crooked posts, and erosion damage. Guardrails in Condition B require 100% maintenance, and the repairs are performed until convenient to the agency's work schedule.

Condition C means that the guardrail has 20-30% deficient length with 70% or more of guardrail length in good condition. Condition C corresponds to a guardrail that has moderate damage which can consist of bent rail, multiple missing posts, or rail deflections that are 12 inches or less. Guardrails in Condition C require 60% maintenance and 40% replacement. These repairs are recommended to be performed no later than a reasonable time frame set by the transportation agency.

The defective condition grade D means that the guardrail system has 30-40% deficient length with 60% or more of the guardrail length in good condition. Condition D corresponds to a guardrail section that has major rail deflections and the same characteristic as noted for guardrail section in Condition C.

Condition F means that the guardrail has more than 40% deficient length with 60% or more of the guardrail section length in good condition. Condition F corresponds to a guardrail

that is severely damaged which may consist of the damage mentioned in the previous section as well as broken gaps within the rail, multiple consecutive missing posts, or consists of rail deflections that are 12 inches or more. Guardrails in Condition F require 100% replacement. The repairs are recommended to be performed no later than the fourth day from the day that the agency receives a work-order or notification.

The following describes the development of the transition matrix used in the guardrail Condition-Based Model.

### **4.3 GUARDRAIL TRANSITION MATRIX**

The likelihood of the transition from one condition category to another is expressed in terms of probabilities in a transition matrix. The deterioration and improvement transition matrix and the increase and decrease in deficient guardrail length are developed using the existing data. The scenarios utilized transition matrices because there was a lack of detailed data and maintenance records that would have been used to develop a straight line deterioration rate. A transition matrix was used in order to use the guardrail condition data that was available. The development of the guardrail transition matrix used in the model is described below.

The inventory provided, by Utah Department of Transportation (UDOT), consisted of General Guardrail Data collected through UDOT. The General Guardrail Data are specifically used for determining the condition of their guardrail system. UDOT utilizes this information to compare their guardrail to the Condition Grade Scale provided in UDOT's Maintenance Management Quality Assurance Plus (MMQA+) program. The General Guardrail Data consisted of 1,066 inventoried guardrails between two years. The data were split into Year 1 and Year 2 data sets. Starting with the Year 1 data, sections with missing inventory parameters such as defective guardrail length and total guardrail length were analyzed. The Year 1 data was then organized by largest to smallest defective guardrail length to eliminate the duplicates and only keep the guardrail length with the highest deficiency. After filtering the data, 217 guardrails were available for analyses for Year 1. The same process was followed for Year 2 inventory. After

filtering Year 2 data, 204 sections were available for analyses for Year 2. To determine the deterioration transition matrix and increase in deficiency within the two years of data, the following, listed in sequential order, was performed.

1. Year 2 inventory was matched to the Year 1 data using the guardrail Station and Section Name. Section and system both refer to the guardrail. Sections that had a higher defective percentage in Year 2 compared to Year 1 represent deterioration and were separated from the rest of the data. In doing so, only 47 datasets consisted of Year 1 and Year 2 data.

The same was performed for determining the improvement transition matrix and the decrease in deficiency. A total of 34 datasets consisted of Year 1 and Year 2 data.

2. The number of guardrails that improved or deteriorated from Year 1 to Year 2 was determined. Table 4.3 shows each of the possible deterioration or improvement transitions.

Table 4.3: Condition Transitions for Deterioration and Improvement

Deterioration Condition Transition	Improvement Condition Transitions
A to A	A to A
A to B	B to A
A to C	B to B
A to D	C to A
A to F	C to B
B to B	C to C
B to C	D to A
B to D	D to B
B to F	D to C
C to C	D to D
C to D	F to A
C to F	F to B
D to D	F to C
D to F	F to D
F to F	F to F

In summary, there are 15 deterioration condition transitions and 15 improvement condition transitions that can be experienced by each of the guardrails in the model. The

following table shows the deterioration condition changes that were recorded between Year 1 and Year 2 for each of the deterioration transitions listed in Table 4.3.

Table 4.4: Deterioration Transition between Year 1 and Year 2

% FROM/ TO	A	B	C	D	F
A	26	7	3	0	3
B		3	3	1	0
C			1	0	1
D				0	1
F					1

Table 4.4 shows the number of guardrail sections that remained in their current condition or deteriorated into a lower condition.

3. The percent condition transition per the total number of guardrails representing deterioration, between Year 1 and Year 2, was determined by dividing each of the values in Table 4.4 by 47 guardrails. The calculated values are provided in Table 4.5.

Table 4.5: Condition Transition Percentage per Total Sections

% FROM/ TO	A	B	C	D	F
A	55%	15%	6%	0%	6%
B		6%	6%	2%	0%
C			2%	0%	0%
D				0%	2%
F					2%

In summarizing Table 4.5, 55% of the guardrails with Condition A in Year 1 remained in Condition A in Year 2 while 15% of guardrails with Condition A in Year 1 deteriorated to Condition B in Year 2.

4. In using Table 4.4, the deterioration transition matrix was determined by dividing the values in each row by the sum of the number of guardrails within its respective row. Table 4.6 shows the transition matrix.

Table 4.6: Deterioration Transition Matrix

% FROM/ TO	A	B	C	D	F
A	67%	18%	8%	0%	8%
B		43%	43%	14%	0%
C			100%	0%	0%
D				0%	100%
F					100%

5. Due to the limited amount of data that presented gaps between condition transitions within the two years of data, the transition matrix values were adjusted. Table 4.7 shows the deterioration transition matrix used in the model for analysis.

Table 4.7: Deterioration Transition Matrix Used for the Model

% FROM/ TO	A	B	C	D	F
A	67%	18%	8%	5%	2%
B		43%	43%	12%	2%
C			35%	40%	25%
D				45%	55%
F					100%

The adjusted transitions were made, based on judgement, to allow for transitions between A and D, C and D, C and D, and F, and D and D to be modeled. The assumption for the model was that from Year 1 and Year 2 there were condition transitions within each condition. Table 4.7 shows that if a guardrail is currently in Condition B, there is a 43% chance that it will remain in Condition B the following year, 43% chance that it will deteriorate to Condition C, 12% chance that it will deteriorate to Condition D, and 2% that it will deteriorate to Condition F.

The same process was followed for the determination of the improvement transition matrix except for those guardrails that had a lower defective percentage in Year 2 compared to Year 1 were separated to represent an improvement in Step 1. Table 4.8 shows the improvement transition matrix used in the model for analysis.

Table 4.8: Improvement Transition Matrix

% FROM/ TO	A	B	C	D	F
A	100%				
B	65%	33%			
C	50%	0%	50%		
D	-	-	-	-	
F	100%	0%	0%	0%	0%

Due to the limited amount of data that presented gaps between a few condition transitions between the two years of data, the transition matrix values were adjusted. Table 4.9 shows the improvement transition matrix used in the model for analysis.

Table 4.9: Improvement Transition Matrix Used for the Model

% FROM/ TO	A	B	C	D	F
A	100%				
B	65%	33%			
C	50%	15%	35%		
D	50%	30%	18%	2%	
F	100%	0%	0%	0%	0%

The transition matrix was adjusted as was done for the deterioration transition matrix. This allowed for transitions between C and B, D to A, D, to B, D to C and D to F to occur. The assumption for the model was that from Year 1 and Year 2 there were condition transitions within each condition. Table 4.9 shows that if a guardrail is currently in Condition D, there is a 50% chance that it will improve to Condition A, 30% chance that it will improve to Condition B, 18% chance that it will improve to Condition C, and 2% that it will remain in Condition D.

Randomness is introduced into the model to incorporate the uncertainty expected in the condition transition process from year<sub>n</sub> to year<sub>n+1</sub>. The randomness is based on the likelihood of the condition transition from one condition category to another. The deterioration and improvement matrix depicts the percent deterioration or improvement, depending if the guardrail is in Condition A, B, C, D, or F. The randomness is a generated number that illustrates the probability of moving from one condition category to another condition category the following year. This number varies by each run for every section and is based on the calculated

probabilities for five different conditions. The magnitude of deterioration and improvement is also obtained from the comparison of the base years. The increase and decrease in guardrail length is determined in Section 4.4.

As was mentioned in the development of the transition matrix, the transition matrix was adjusted to provide transitions for each of the 30 condition transitions. Inventory collected spanning over a number of years can result in data that model the existing conditions accurately. Consecutive yearly inventory can be further analyzed, averaged, and used to develop trends. This information can be used to develop the transition matrix and increase the accuracy of the transition matrix to model true deterioration and improvement patterns.

#### **4.4 INCREASE AND DECREASE IN GUARDRAIL LENGTH DEFICIENCY**

The increase and decrease in deficient guardrail length is represented by a percentage developed using the average condition percentage for each of the deterioration scenarios that can take place within a year, provided in Column 1 of Table 4.10. For example, a guardrail in Condition A can remain in Condition A the following year or can deteriorate to Condition B, C, D, or F. The increase in deficient guardrail length was determined by calculating the difference between Year 2 and Year 1 average condition percentage. The Year 1 average condition percentage, listed in Column 2 of Table 4.10, was determined by averaging the deterioration condition percentage for each deterioration condition scenario listed in Column 1. Since the data provided were limited and successive yearly data were not available, it was assumed that the same guardrail sections that deteriorated in Year 1 also deteriorated in Year 2. This assumption was used to determine the Year 2 average condition percentage. The percent increase in deficient guardrail length, used in the model, is listed in Column 4 of Table 4.10.



Table 4.10: Information to Determine Percent Increase in Deficient Guardrail Length

Column 1	Column 2	Column 3	Column 4
Condition Transition	Year 1 Average Condition Percentage	Year 2 Average Condition Percentage	Percent Increase in Deficient Guardrail Length
A to A	2.44%	4.18%	1.74%
A to B	4.99%	13.72%	8.73%
A to C	3.46%	23.49%	20.03%
A to D	3.74%	38.92%	35.18%
A to F	4.01%	54.35%	50.34%
B to B	12.42%	16.43%	4.01%
B to C	14.15%	22.98%	8.83%
B to D	12.55%	36.41%	23.86%
B to F	10.95%	49.84%	38.89%
C to C	23.56%	26.03%	2.47%
C to D	26.86%	39.47%	12.61%
C to F	30.16%	52.91%	22.75%
D to D	33.46%	53.38%	19.92%
D to F	36.70%	79.79%	43.09%
F to F	48.02%	53.85%	5.83%

Column 4 of Table 4.10 represents the possible percent increase in deficient guardrail length that occurs between one analysis year to another. The same process was used to the percent decrease in deficient guardrail length. The Year 1 average condition percentage was subtracted from the Year 2 average condition percentage to determine the percent decrease in deficient guardrail length listed in Column 4 of Table 4.11.

Table 4.11: Information to Determine Percent Decrease in Deficient Guardrail Length

Column 1	Column 2	Column 3	Column 4
Condition Transition	Year 1 Average Condition Rate	Year 2 Average Condition Rate	Percent Decrease in Deficient Guardrail Length
A to A	3.20%	1.61%	-1.59%
B to A	13.24%	4.36%	-8.88%
B to B	13.27%	12.14%	-1.13%
C to A	22.27%	4.19%	-18.08%
C to B	26.00%	11.41%	-14.59%
C to C	29.88%	26.58%	-3.29%
D to A	34.28%	29.69%	-4.58%
D to B	38.68%	32.81%	-5.87%
D to C	43.08%	35.92%	-7.16%
D to D	47.48%	39.03%	-8.45%
F to A	52.15%	42.15%	-10.00%
F to B	56.55%	45.26%	-11.29%
F to C	60.95%	48.37%	-12.58%
F to D	65.35%	51.48%	-13.87%
F to F	69.75%	54.59%	-15.16%

Table 4.7 and Column 4 of Table 4.10 were condensed into Table 4.12. Table 4.12 shows the deterioration probability and the corresponding percent decrease in deficient guardrail length referred to as percent deterioration. The current condition of each section affects the future condition of that section. For example, a guardrail section in Condition A requires no maintenance activities to be performed therefore a section in Condition A will remain in Condition A or deteriorate to Condition B, C, D, and F with a probability of 67%, 18%, 8%, 5%, and 2% respectively with a percent deterioration of 1.7%, 10.3%, 20.0%, 35.2%, and 35.2% respectively. A guardrail section in Condition D will remain in Condition D or deteriorate to Condition F with a probability of 45%, and 55% respectively with a percent deterioration rate of 19.9% and 43.1% respectively.

Table 4.12: Condition Deterioration Transition Matrix

	<b>A</b>		<b>B</b>		<b>C</b>		<b>D</b>		<b>F</b>	
	Deterioration	Probability	Deterioration	Probability	Deterioration	Probability	Deterioration	Probability	Deterioration	Probability
<b>A</b>	1.7%	67%	10.3%	18%	20.0%	8%	35.2%	5%	35.2%	2%
<b>B</b>			4.0%	43%	10.3%	43%	23.9%	12%	38.9%	2%
<b>C</b>					2.5%	35%	12.6%	40%	22.75%	25%
<b>D</b>							19.9%	45%	43.1%	55%
<b>F</b>									5.8%	100%

Table 4.9 and Column 4 of Table 4.11 were condensed into Table 4.12. Table 4.12 shows the improvement probability and the corresponding percent decrease in deficient guardrail length referred to as percent improvement. The current condition of each section affects the future condition of that section. For example, a guardrail section in Condition D can remain in Condition D or improve to Condition C, B, or A with a probability of 2%, 35%, 15%, and 50% respectively with a percent improvement rate of 8.5%, 10%, 20.1%, and 30% respectively.

Table 4.13: Condition Improvement Transition Matrix

	<b>A</b>		<b>B</b>		<b>C</b>		<b>D</b>		<b>F</b>	
	Improvement	Probability	Improvement	Probability	Improvement	Probability	Improvement	Probability	Improvement	Probability
<b>A</b>	1.6%	100%								
<b>B</b>	10.0%	67%	1.1%	33%						
<b>C</b>	20.0%	50%	14.6%	15%	3.3%	35%				
<b>D</b>	30.0%	50%	20.1%	30%	10.0%	18%	8.5%	2%		
<b>F</b>	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%

#### 4.5 SCENARIOS WITHIN THE MODEL

Each scenario provides the agency the ability to forecast the guardrail network conditions as well as financial consequences resulting from delayed maintenance and limited budget. Six scenarios, defined in Section 3.6, are used as runs in the Condition-Based Model to achieve the forecasting reports beneficial to the agency.

As was mentioned in Section 3.6.1, Scenario 1, depicts a situation where maintenance and replacement activities are carried out for each guardrail in Condition B, C, D, and F using the decision criteria previously described in Section 4.4. Scenario 1 is the desired scenario and is referred to as the “All Needs” scenario because the guardrails are maintained and are kept in good condition. This scenario allows for the agency to determine the funding necessary to carry out the maintenance activities to keep the guardrail system in acceptable condition.

In Scenario 2, also referred to as the “Do-Nothing” scenario, models the consequences of allocating zero funding or resources to perform any maintenance and replacement. Scenario 2 is known as the worst case scenario because the model assumes that no preservation policies are enforced, and the entire network deteriorates.

Scenarios 3 and 4 models delayed maintenance and replacement that result from policy enforcement or limited budget. Delayed maintenance resulting from policy enforcement is modeled by the delayed time, Z. If the guardrail section requires maintenance in year X, then the proposed maintenance activity is differed by Z years. Z years are set at 1 and 3 years.

Delayed maintenance resulting from limited budget constraints are modeled by delaying maintenance activities until the necessary funds become available. In scenario 3 and 4, guardrail maintenance priorities are based on a Maintenance Priority Index (MPI) to prioritize guardrail section requiring maintenance activities as soon as funding becomes available. The MPI is dependent on the average daily traffic (ADT), length of the guardrail section, and is used until the funds become exhausted. The following will provide an example of how Scenario 1 the model to provide results.

If the guardrail section is 67% deficient, which corresponds to Condition F, the probability that the section will go to Condition A is 100%. It is for this reason that the condition will improve by 100% and the percent condition will be set to 0% deficiency which corresponds to Condition A. At the beginning of the following analysis year, this section will be at Condition A. If the section is in Condition B, C, or D, the original percent deficiency is then added to a random improvement rating that is randomly calculated. Therefore, the section can remain in its

current condition or improve. Guardrail sections in Condition F will automatically improve to Condition A. The condition at the end of year 1 then becomes the condition at the beginning of year 2 and the process is repeated through the rest of the analysis years.

The results at the end of the 10-year analysis include the guardrail system value and the percentage of guardrails in each of the condition, as well as the corresponding cost needed for that analysis year.

The following chapter describes a case study that was performed to test the model. The results are explained as well.

#### **4.6 IMPACTS OF GUARDRAIL CONDITION AND CRASH RATES**

Based on location, weather, and other factors, a roadway crash involving a guardrail can result in a crash involving property damage, possible injury, non-incapacitating injury, incapacitating injury, or a fatality (NSC, 2015). Driver behavior, vehicle characteristics and roadway features are three major factors that are associated with fatal vehicle crashes (TRIP, 2014). In efforts to further the Condition-Based Model, the addition of crash related information could be used to determine key information. This information could include, crash rates, crash cost, and the funding associated with the guardrail system's condition over a 10-year analysis.

An attempt was made to calculate a crash rate using the Colorado DOT (CDOT) method highlighted in "Crashes and Rates on State Highway" 2011 document. Table 4.14 lists the equations used to determine the Total Crash Rate ( $R_s$ ).

Table 4.14: Equations to Determine Total Crash Rate ( $R_s$ )

Number of crashes in an individual highway section	$A_i$
Number of total crashes in the combined section	$A_s = \sum A_i$
Individual section length (miles to two decimal places)	$L_i$
Length of combined section	$L_s = \sum L_i$
Individual section Average Daily Traffic Volume	$ADT_i$
Combined section Average Daily traffic Volume	$ADT_s = \sum \frac{(ADT_i)(L_i)}{L_i}$
Total Crash Rate for the combined section per million vehicles or per million	$R_s = \frac{(A_s)(1,000,000)}{(365)(L_s)(ADT_s)}$

Source: CDOT, 2011

Refer to Section 5.2 for a case study used to determine a Total Crash Rate and Crash Cost for Scenario 1 and 3a.

## Chapter 5: Case Study - Application of the Guardrail Asset Management Framework

### 5.1 CONDITION-BASED MODEL

An inventory of 650 miles, provided by Utah Department of Transportation (UDOT), was used to illustrate the application of the performance-based model for asset management practices. The data provided included general data, accident data, work order and inspection data, and new installation data. The data provided were included for multiple guardrails or sections within a guardrail network. Figure 5.1 illustrates the inventory collected from each of the data excel files received.

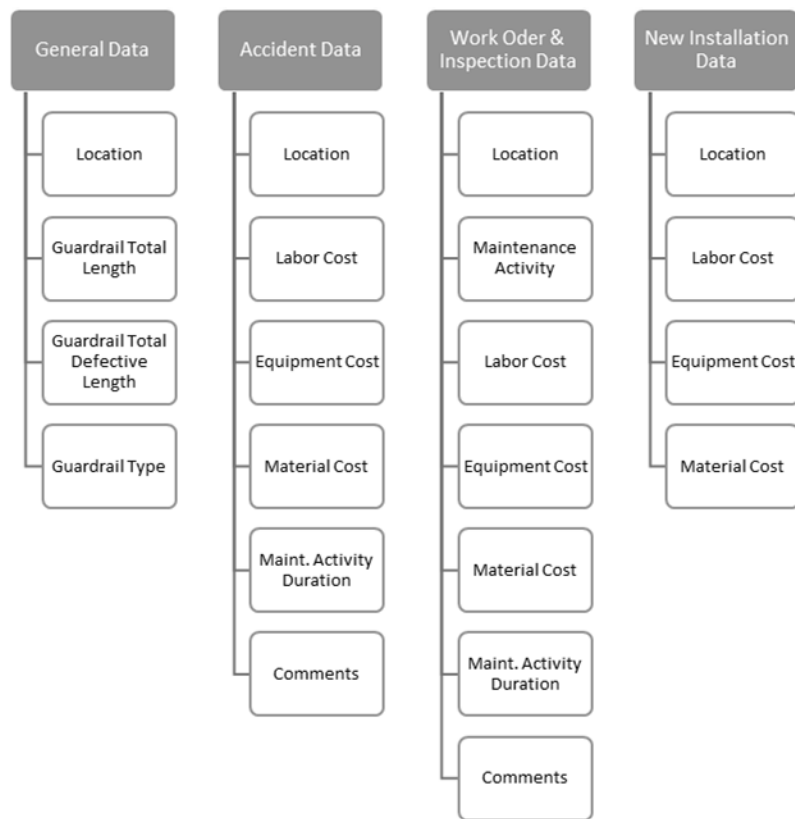


Figure 5.1: Data used in Transition Matrix and Case Study

The challenge in using the provided data was that it was only two years of data. Due to limited data, it was difficult to achieve a large dataset that are linked to the four types of data to best utilize the entire dataset.

Figure 5.1 provides a visual representation of the percentage of the guardrails in Conditions A, B, C, D, and F.

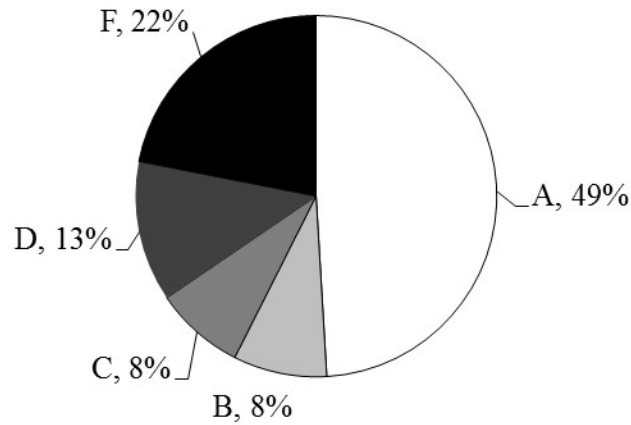


Figure 5.2: Guardrail Condition at the Beginning of the Analysis

As shown in Figure 5.1, 49% of the guardrail system is in Condition A and 22% is in Condition F. The condition of each section at the end of the analysis year is not only dependent on the current condition, but also on budget availability. Applying the appropriate maintenance or necessary replacement is not only critical but also impacts the end of year condition of the entire guardrail network. Each scenario utilizes decision criteria that are dependent on the condition of each guardrail and the ADT. The results produced from the 10-year analysis period are provided in Table 5.1.



Table 5.1: Case Study Results

	Scenario	Agency Costs for Total Work Performed End of Year 10 ( \$M)	Unfunded Backlog Cost at the End of End of Year 10 ( \$M)	Percent of Guardrail with more than 40% Deficient Length (Condition F)	
				Beginning	End of Year 10
1	All Needs	\$29.42	\$0.00	22%	2%
2	Do-Nothing	\$0.00	\$290.60	22%	100%
3a	Delay Maintenance activities by 1 Year	\$40.35	\$23.98	22%	6%
3b	Delay Maintenance activities by 3 Years	\$41.03	\$82.09	22%	24%
4a	Delay Maintenance due to Limited Budget (80% of Baseline)	\$23.00	\$74.47	22%	30%
4b	Delay Maintenance due to Limited Budget (60% of Baseline)	\$17.14	\$129.34	22%	43%

Table 5.1 lists each of the scenarios and their corresponding agency costs, unfunded backlog, and the percentage of guardrail in Condition F at the beginning and the end of the 10-year analysis. In modeling Scenario 1, the guardrail system results with 2% of the guardrail system in Condition F. Within the 10-years analysis period, \$29.42M would have to be invested to provide continuous yearly maintenance and repair and procure no unfunded backlog. In modeling scenario 2, which models the complete opposite of Scenario 1, the guardrail system results in 100% of the guardrail system in Condition F. Within the 10-year analysis, the agency would not have spent any funding towards the guardrail system but would procure \$290.60M in unfunded backlog costs.

Scenario 3a results in 6% of the guardrail system in Condition F at the end of the 10-year analysis. By delaying maintenance by one year when the guardrail requires maintenance, the agency cost results in \$40.35M, with \$23.98M in unfunded backlog costs.

Scenario 3b results in 24% of the guardrail system in Condition F at the end of the 10-year analysis. By delaying maintenance by three years when the guardrail requires maintenance,

the agency cost results in only 1.69% more in agency costs and more than triples in unfunded backlog costs compared to Scenario 1.

Scenario 4a results in 30% of the guardrail system in Condition F at the end of the 10-year analysis. In utilizing 80% of the baseline budget of \$29.42M, the agency can only spend \$23M at the end of the 10-year analysis. As a result \$74.47M in unfunded backlog costs procures.

Scenario 4b results in 43.33% more of guardrail system in Condition F compared to Scenario 4a. This corresponds to \$17.14M in agency costs and \$129.34 in unfunded backlog costs. The comparison between Scenario 4a and 4b concludes that as the available funding are cut-back, the backlog increases. As can be seen in Table 5.1, the agency costs used in Scenarios 4a and 4b do not equate to 80% or 60% of the agency costs listed in Scenario 1. Since the model utilizes randomness, Scenario 4a and 4b agency costs do not equate to the following: 80% of \$29.42M is equal to \$23.54M while 60% of \$29.42M is equal to \$17.65M.

Figure 5.3 shows the condition of the guardrail network at the end of the 10-year analysis period for Scenario 1 and 2.

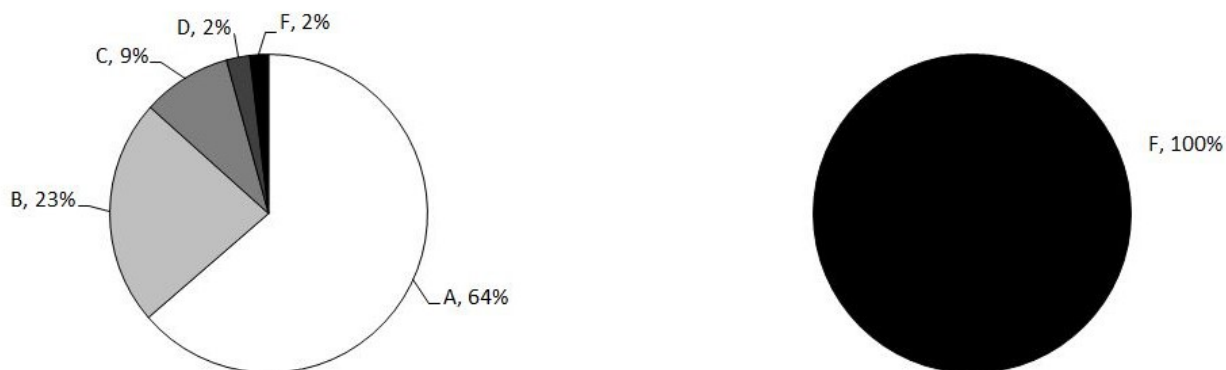


Figure 5.3: Scenario 1 (Left) and 2 (Right): Guardrail System Condition, Year 10

Scenario 1 results show that two thirds of the system is in Condition A and B. Scenario 2 produces the worst results with no sections in Condition A, which is expected because Scenario 2

models a scenario that includes no maintenance and repair activities. Figure 5.4 and 5.5 shows the maintenance delay and the funding constraint scenarios 3a, 3b, 4a, and 4b.

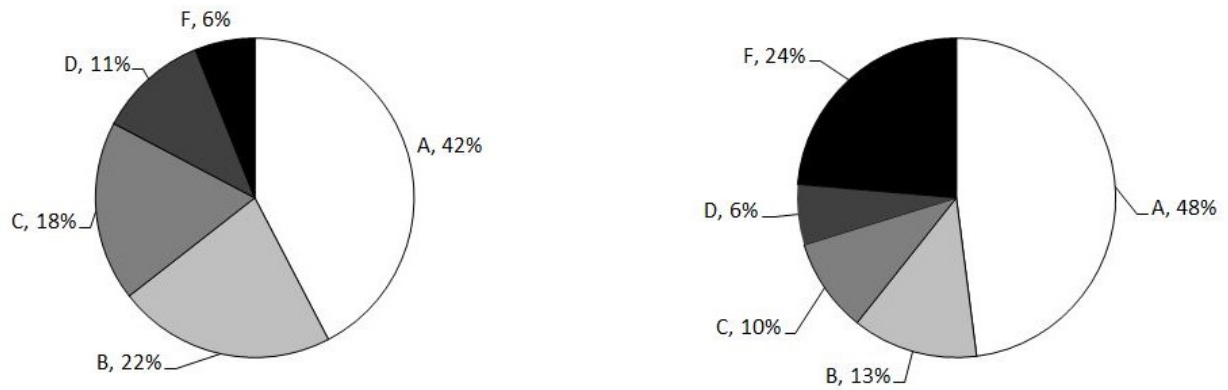


Figure 5.4: Scenario 3a (Left) and 3b (Right): Guardrail System Condition, Year 10

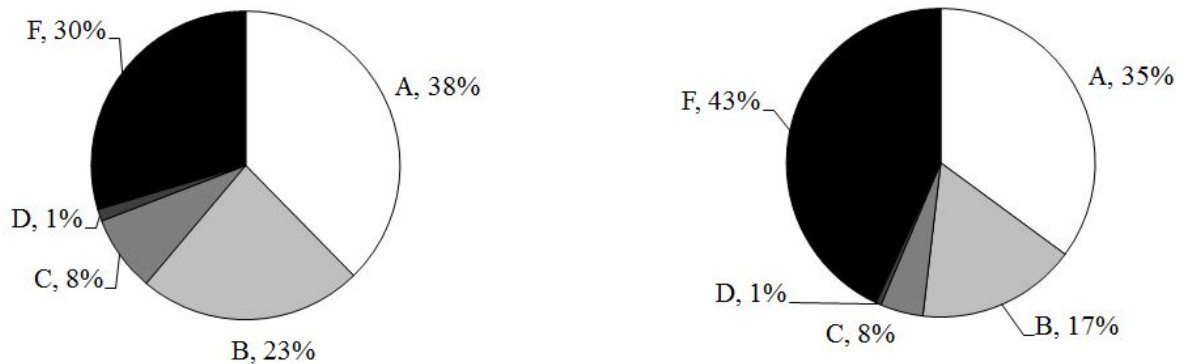


Figure 5.5: Scenario 4b (Left) and 4b (Right): Guardrail System Condition, Year 10

Scenario 3a, 3b, 4a, and 4b, end of 10-year condition results clearly show how each of the scenarios are impacted by the maintenance and replacement activities fund constraints applied to the model.

The following figures display the changes in condition within the 10-year analysis for each of the scenarios.

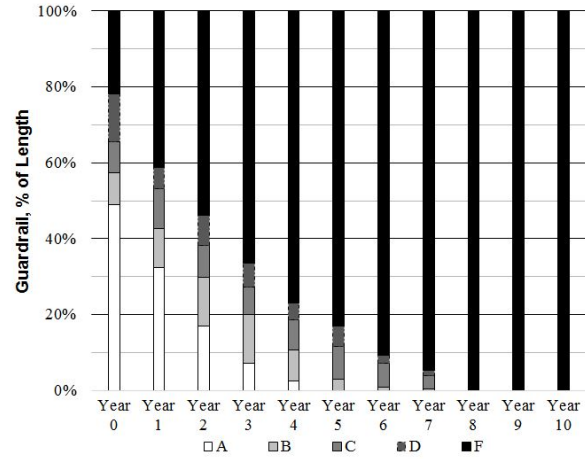
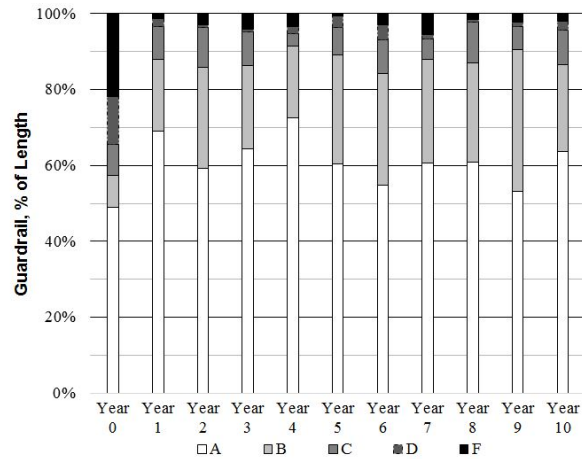


Figure 5.6: Scenario 1 (Left) and 2 (Right): Guardrail System Condition for each Year

Scenario 1 is mostly A and B during the entire period of analysis with less guardrails in Condition F and D when compared to the other scenarios. Scenario 2 results show complete opposite situation as what was previously summarized for Scenario 1. Starting in Year 5, a large majority of the guardrail system is in Condition F, and none of it is in Condition A.

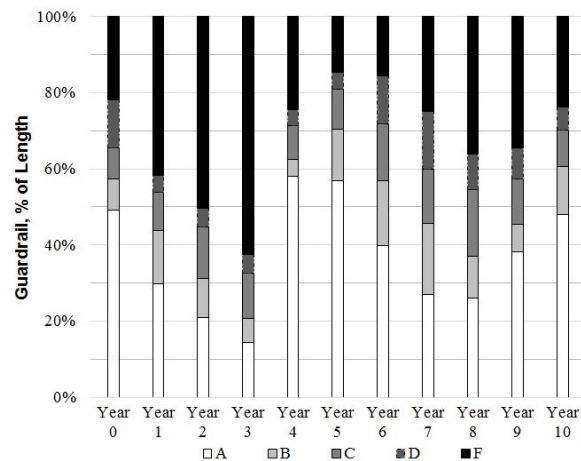
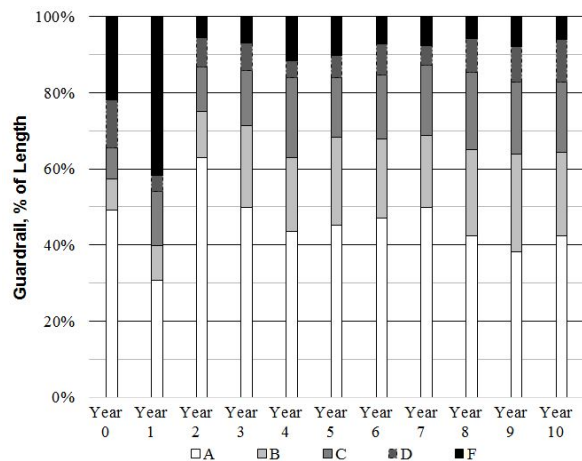


Figure 5.7: Scenario 3a (Left) and 3b (Right): Guardrail System Condition for each Year

In scenarios 3a and 3b, there is a large drop in the overall guardrail condition due to the delayed maintenance. It can be seen that the guardrail system tries to recuperate but does not show a

consistent increase in the percentage of the guardrail system in Condition A within the 10-year analysis.

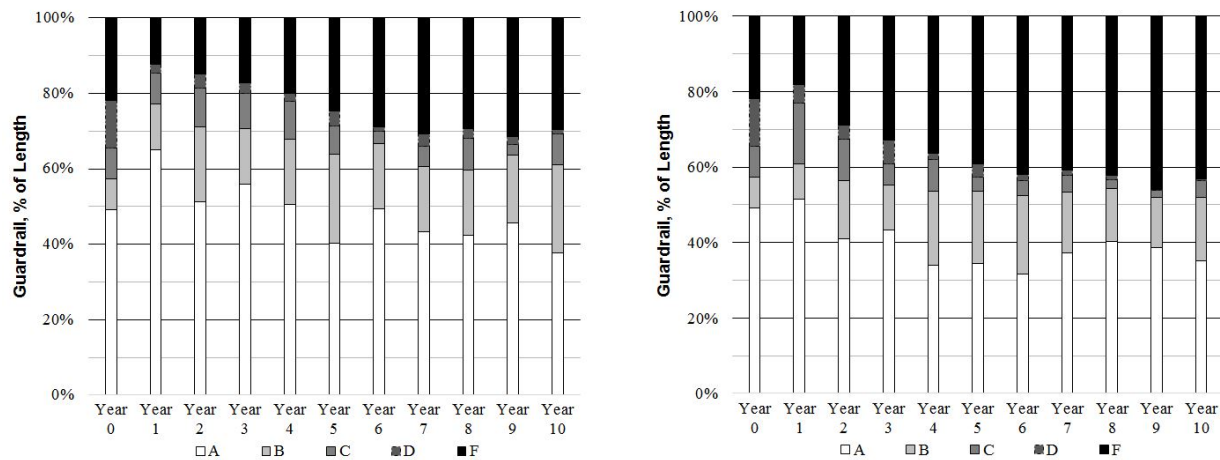


Figure 5.8: Scenario 4a (Left) and 4b (Right): Guardrail System Condition for each Year

Scenario 4a has no more than one-third of the system in Condition F, while half of the entire system is Condition F in Scenario 4b during the 10-year analysis.

The following figures display the unfunded backlog for each of the scenarios within the 10-year analysis.

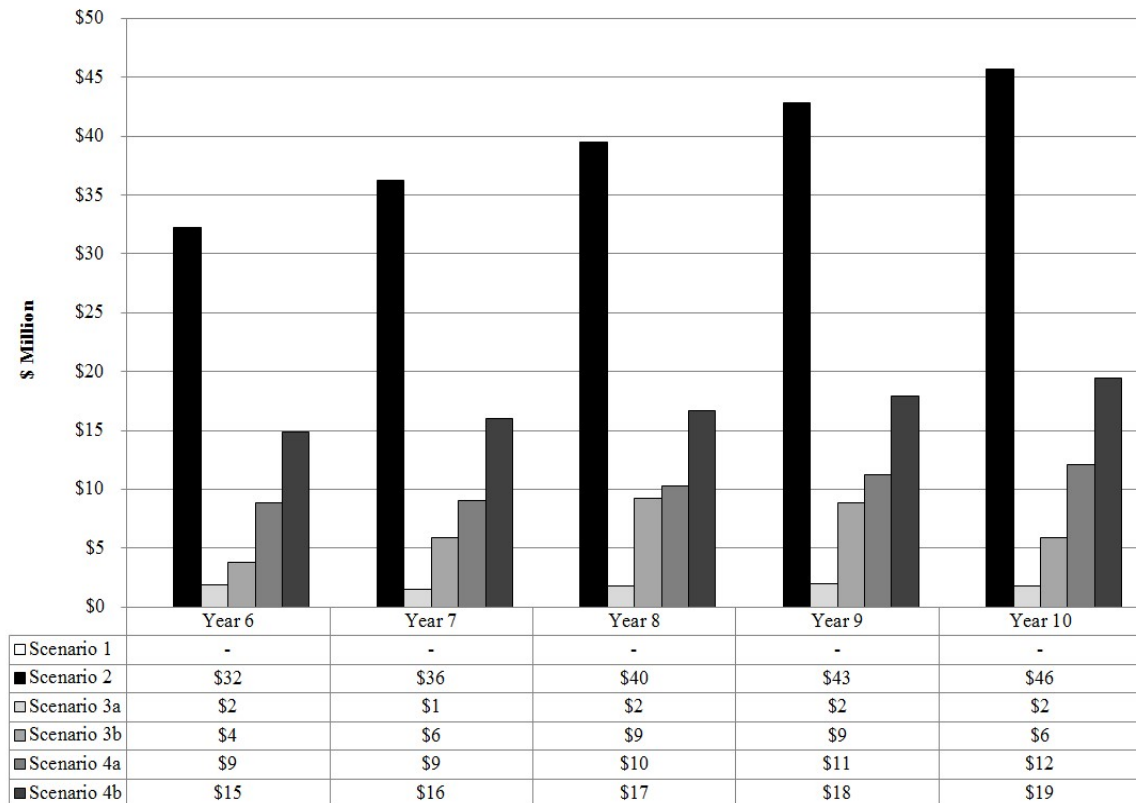
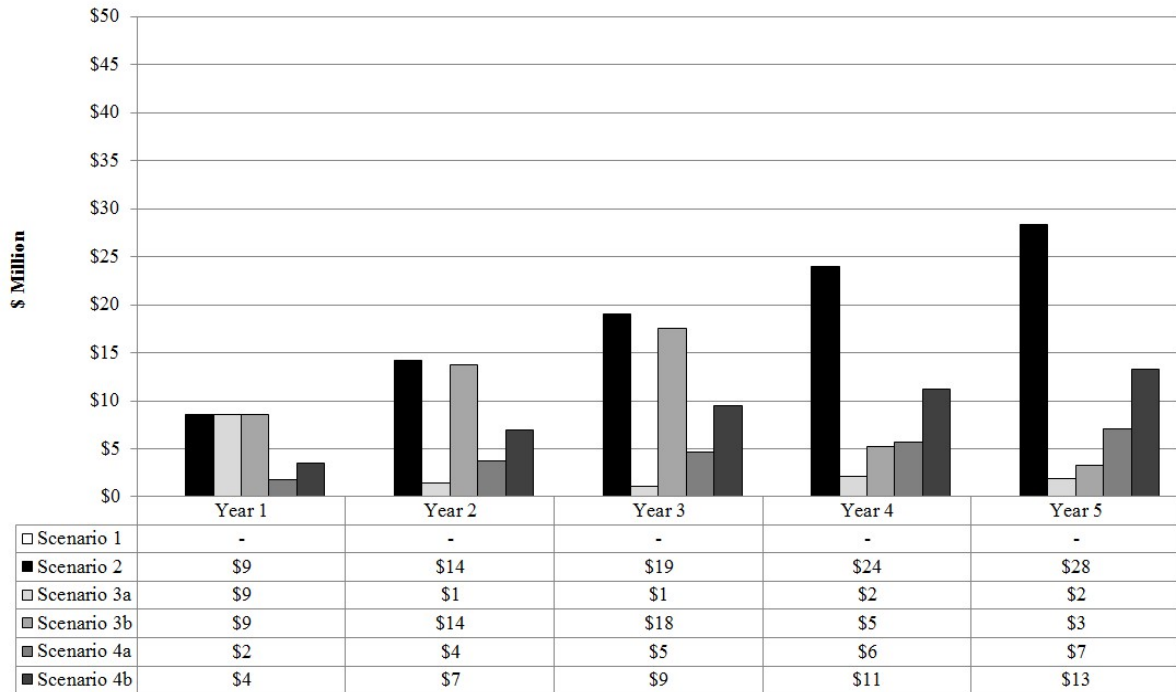


Figure 5.9: Unfunded Backlog for each Scenario, Years 1 through 10

There is no unfunded backlog for Scenario 1 due to the absence of any restrictions regarding budget costs and maintenance and replacement activities. The highest backlog is produced in Scenario 2 which begins with \$9M in the first year and results in \$46M at the end of year 10. Scenario 3a starts with the same backlog as Scenario 2 and fluctuates between \$1M and \$2M throughout the analysis period. Scenario 3b fluctuates between \$9M and \$3M and results in \$6M at year 10. Scenario 3a and 3b results may be attributed to the consistent maintenance and replacement activity delays. The system partially reciprocates meaning that the backlog decreases and then increases. The backlog for scenario 4a shows a gradual increase from \$2M to \$19M on the last year. Scenario 4b follows a similar trend but from \$4M to \$19M of unfunded backlog.

Figures 5.10 through 5.15 show the Guardrail System Value (GSV) and Guardrail Sustainability Ratio (GSR) over the analysis period for each of the scenarios.

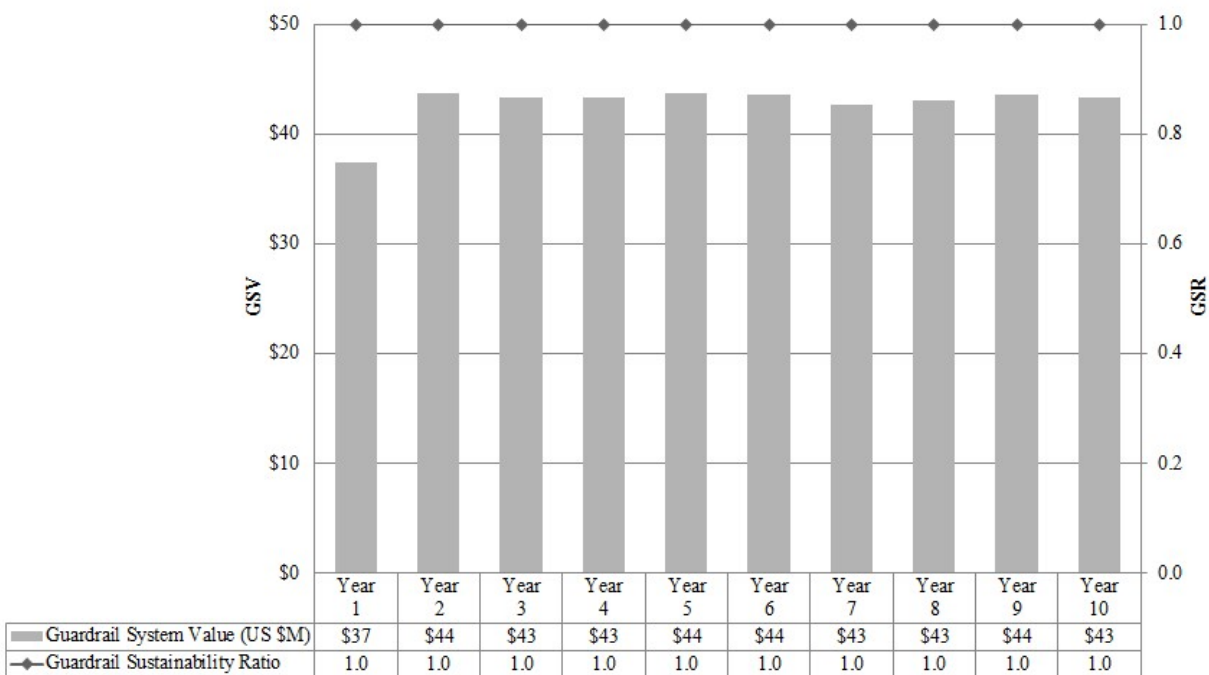


Figure 5.10: Scenario 1 – Guardrail System Value and Guardrail Sustainability Ratio

Scenario 1 has the highest GSV at \$37M at the beginning of the analysis and increases to \$43M at the end of the analysis period. Scenario 1 results in a GSR of 1.0 throughout the entire analysis period. Scenario 1 results are expected due to the available funds and resources, therefore, the value of the network continues to increase throughout the years.

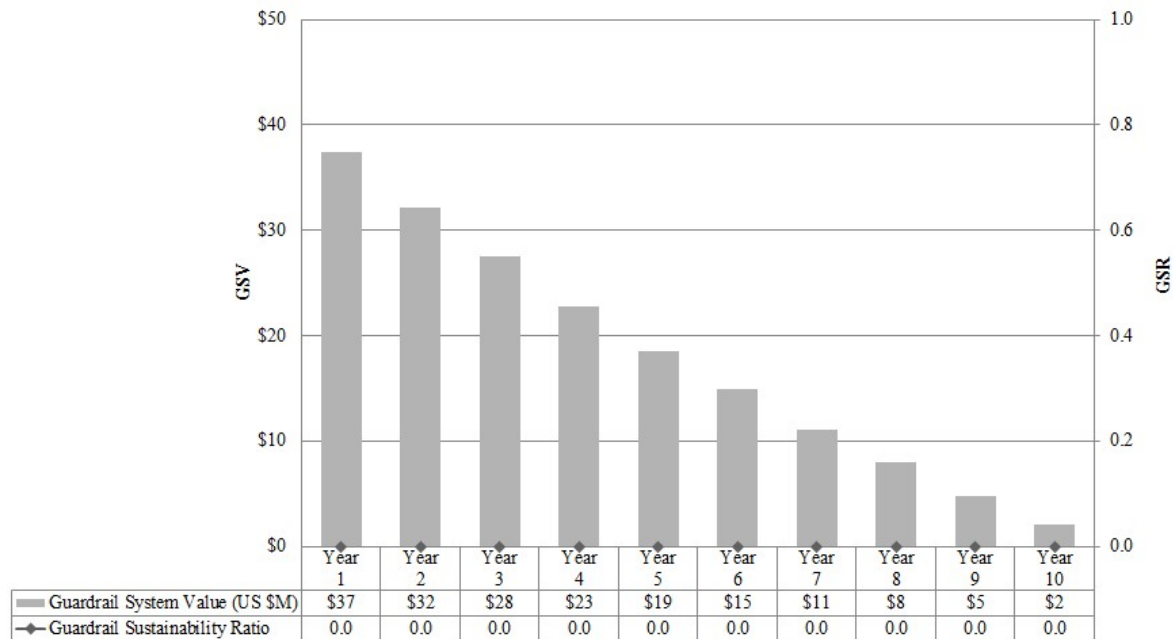


Figure 5.11: Scenario 2 – Guardrail System Value and Sustainability Ratio

In Scenario 2, the GSV consistently goes down to \$2M in the last year. Scenario 2 results in a GSR of 0.0 as expected due to the lack of funds available to take care of the necessary maintenance and replacement.





Figure 5.12: Scenario 3a – Guardrail System Value and Guardrail Sustainability Ratio

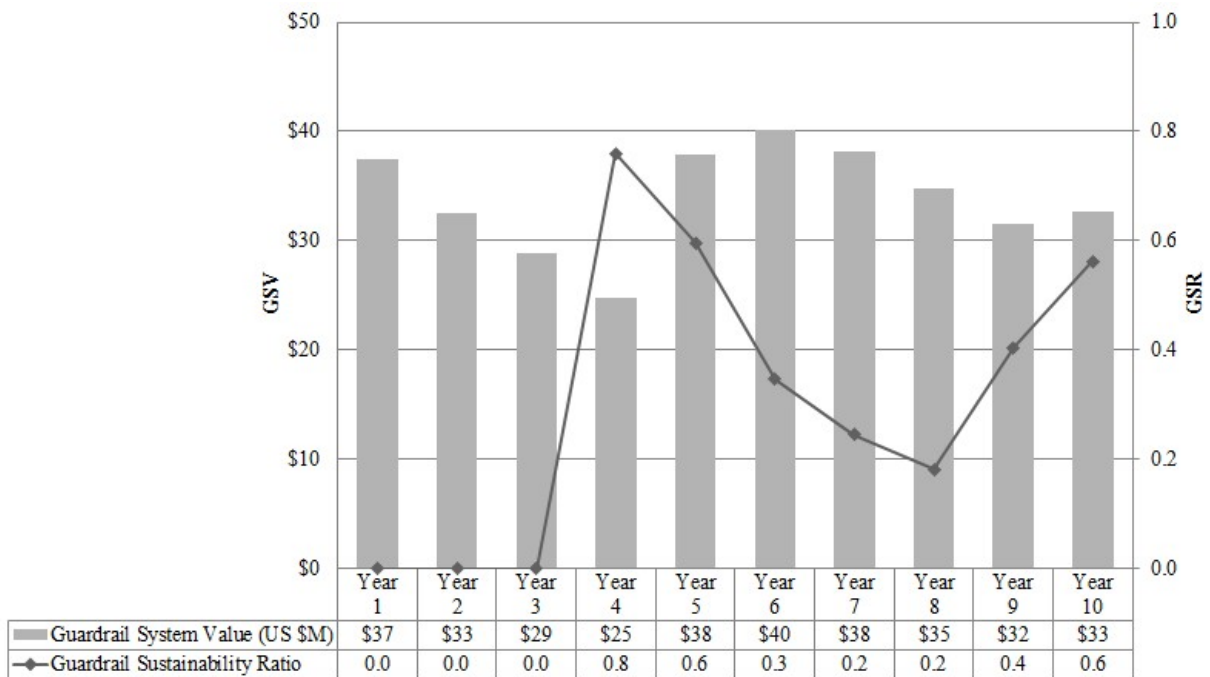


Figure 5.13: Scenario 3b – Guardrail System Value and Guardrail Sustainability Ratio

The GSV for Scenarios 3a and 3b fluctuates throughout the analysis and results in \$40M and \$33M respectively. As is expected, the delayed maintenance at the beginning of the analysis period impacts the entire analysis because as the guardrails are maintained, the following year results in delayed maintenance.

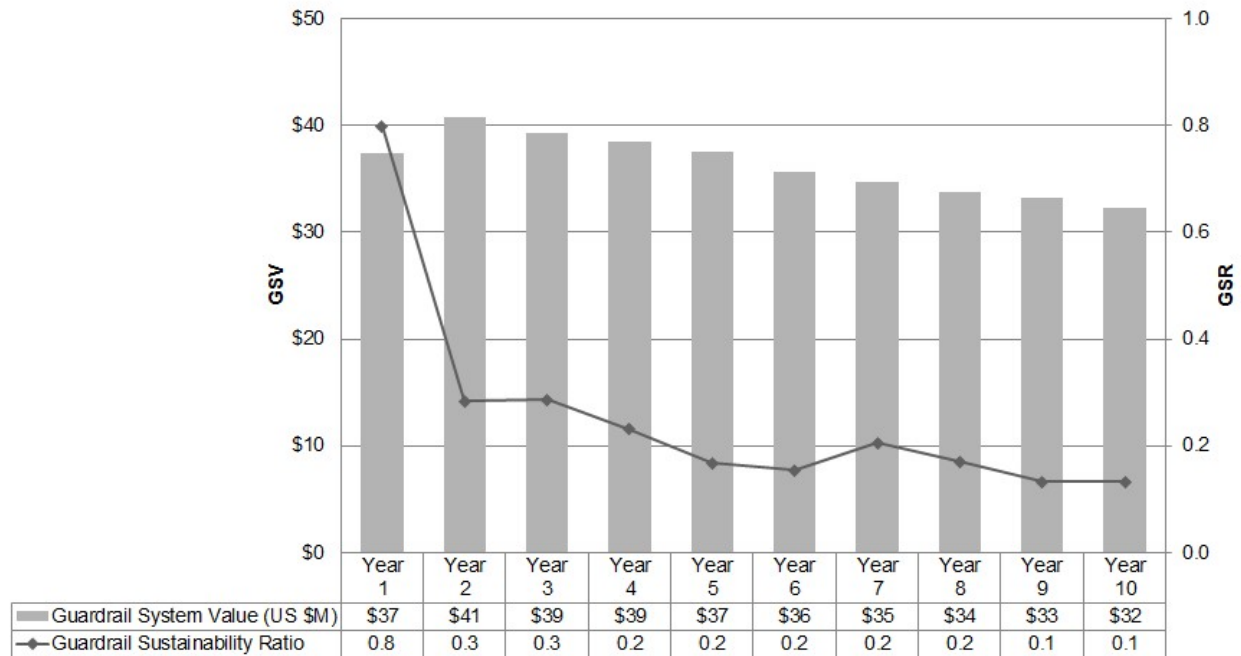


Figure 5.14: Scenario 4a – Guardrail System Value and Guardrail Sustainability Ratio

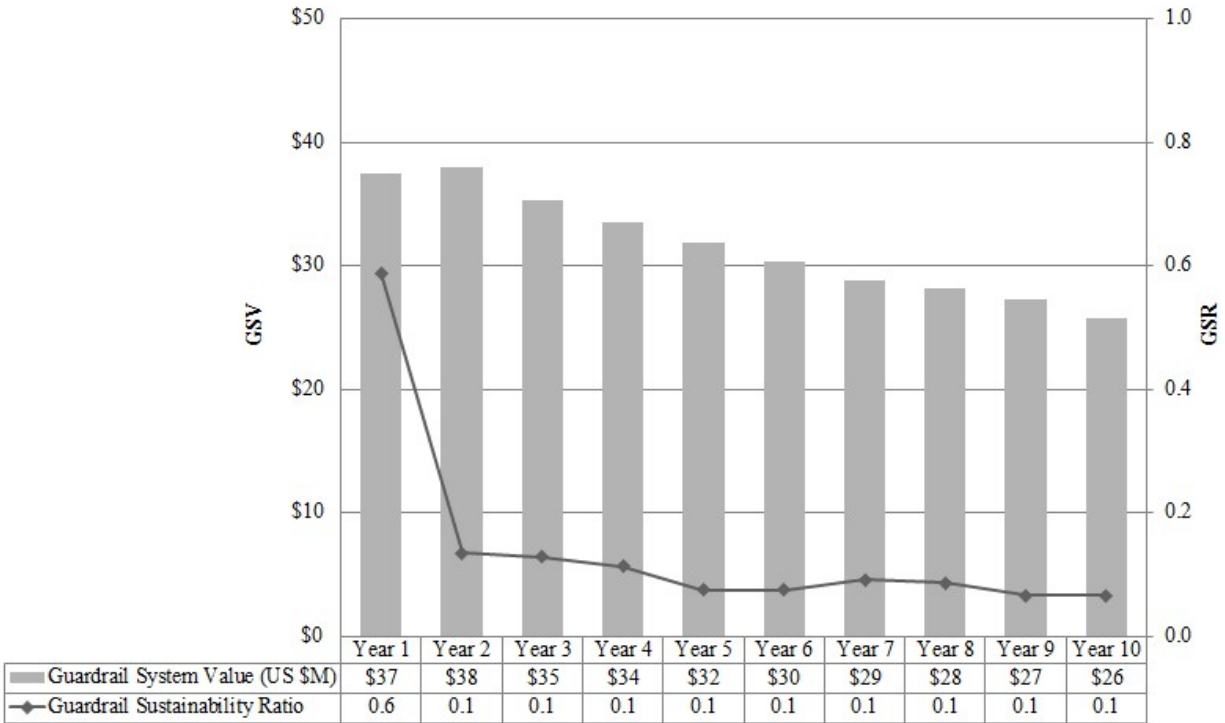


Figure 5.15: Scenario 4b – Guardrail System Value and Guardrail Sustainability Ratio

The GSV for Scenarios 4a and 4b steadily decreases to \$32M and \$26M, respectively, at the end of the analysis period. As is expected, the budget constraints for Scenario 4a and 4b results in the guardrail network depreciating.

## 5.2 CRASH COST MODEL

The following describes a process that utilizes the calculation of the Total Crash Rate and the Total Crash Costs to develop a Crash Cost Model. The methodology requires additional research but is provided to show the preliminary findings for the recommendations.

Using the Utah DOT (UDOT) data available, the calculated  $A_s$ ,  $L_s$ ,  $ADT_s$ , and  $R_s$  introduced in Section 4.6, are as listed in Table 5.2.

Table 5.2: Calculated Information to Determine the Total Crash Rate ( $R_s$ )

Number of total crashes in the combined section	$A_s = \sum A_i$	968
Length of combined section	$L_s = \sum L_i$	3,023
Combined section Average Daily traffic Volume	$ADT_s = \sum \frac{(ADT_i)(L_i)}{L_i}$	10,283
Total Crash Rate for the combined section per million vehicles	$R_s = \frac{(A_s)(1,000,000)}{(365)(L_s)(ADT_s)}$	0.085

Source: CDOT, 2011

In determining  $A_s$ , an assumption had to be made based on a CDOT Total Crash Rate performed for 3 sections that included 33 crashes. Based on our data, we had 88 sections, therefore, it was assumed that based on a ratio of 33 crashes per 3 sections, the data would include 968 crashes within 88 sections. This would require more data collection to determine the actual number of crashes within the sections in question. Our assumption is based on a ratio and does not incorporate any information about location, and geometry of the road which would greatly impact the number of crashes that could occur within a section.

Table 5.3 lists the total crash cost provided by the National Safety Council, associated with the damage type that can occur during a crash involving a guardrail.

Table 5.3: Economic and Comprehensive Crash Costs

Crash Type	Crash Cost		
	Economic	Comprehensive	Total Crash
Property Damage Only	\$9,300	\$2,600	\$11,900
Possible Injury	\$13,600	\$28,600	\$42,200
Non-incapacitating Injury	\$24,000	\$60,000	\$84,000
Incapacitating injury	\$74,900	\$235,400	\$310,300
Fatality	\$1,500,000	\$4,628,000	\$6,128,000

Source: NSC, 2015

The condition associated with the damage type and crash cost was determined by incorporating the Condition Grade Scale used in the Condition-Based Model. Table 5.4 provides the Crash Type and the associated guardrail condition.

Table 5.4: Crash Cost and Associated Condition

Crash Type	Condition	
	Good (A-D)	Poor (F)
Property Damage Only	90%	10%
Possible Injury	80%	20%
Non-incapacitating Injury	70%	30%
Incapacitating injury	60%	40%
Fatality	< 60%	> 40%

Based on Table 5.4, it is assumed that an accident that occurs at a guardrail in condition A involves the probability that the accident can occur in 90% of the guardrail section that is in good condition or in 10% of the guardrail that is in poor condition.

Table 5.5 lists the percentages of guardrail within each condition from Year 1 to Year 10 for Scenario 3a which includes a 1 Year maintenance and repair delay.

Table 5.5: Guardrail Condition over the 10-Year Analysis

Year	A	B	C	D	F
1	31%	9%	14%	4%	42%
2	63%	12%	12%	8%	6%
3	50%	22%	14%	7%	7%
4	44%	19%	21%	5%	12%
5	45%	23%	15%	6%	10%
6	47%	21%	17%	8%	7%
7	50%	19%	18%	5%	8%
8	42%	23%	20%	9%	6%
9	38%	26%	19%	9%	8%
10	42%	22%	18%	11%	6%

In utilizing Table 5.5 and the calculated Total Crash Rate ( $R_s$ ), a Crash Rate for each of the Conditions was determined. The Crash Rate for each condition is listed in Table 5.6.

Table 5.6: Crash Rate for Each Condition

Year	R <sub>SA</sub>	R <sub>SB</sub>	R <sub>SC</sub>	R <sub>SD</sub>	R <sub>SF</sub>
1	0.026	0.008	0.012	0.004	0.036
2	0.054	0.010	0.010	0.007	0.005
3	0.043	0.018	0.012	0.006	0.006
4	0.037	0.016	0.018	0.004	0.010
5	0.039	0.020	0.013	0.005	0.009
6	0.040	0.018	0.014	0.007	0.006
7	0.043	0.016	0.016	0.004	0.006
8	0.036	0.019	0.017	0.008	0.005
9	0.033	0.022	0.016	0.008	0.007
10	0.036	0.019	0.016	0.010	0.005

To further simplify the Table 5.6, R<sub>SA1</sub> is equal to 0.026. This means that the Crash Rate for Condition A in Year 1 is 0.026. The Crash Rate for Condition D in Year 9 (R<sub>SD9</sub>) is equal to 0.008.

In utilizing the Crash Rates listed in Table 5.6 and the Crash Costs provided in Table 5.3, the Crash Cost for each condition was determined. The Crash Cost for each condition is provided in Table 5.7.

Table 5.7: Crash Cost for each Condition

Year	CC <sub>SA</sub>	CC <sub>SB</sub>	CC <sub>SC</sub>	CC <sub>SD</sub>	CC <sub>SF</sub>
1	\$16,300	\$9,781	\$23,355	\$9,417	\$93,710
2	\$33,485	\$13,061	\$18,934	\$8,198	\$12,544
3	\$26,505	\$23,141	\$23,399	\$7,901	\$15,378
4	\$23,222	\$20,624	\$34,015	\$4,976	\$25,900
5	\$24,036	\$24,965	\$25,051	\$6,434	\$22,774
6	\$25,039	\$22,344	\$27,349	\$8,701	\$16,078
7	\$26,556	\$20,166	\$29,905	\$5,647	\$17,065
8	\$22,560	\$24,307	\$32,964	\$9,537	\$12,898
9	\$20,356	\$27,432	\$30,922	\$10,037	\$17,467
10	\$22,535	\$23,753	\$29,521	\$12,043	\$13,702

CC<sub>SA1</sub> is the Crash Cost associated with the guardrails that are in Condition A in Year 1 and is calculated as follows,  $CC_{SA1} = (R_{SA1} * 90\% * \$11,900) + (R_{SA1} * 10\% * \$6,128,000)$ . These results takes into account the crash rate calculated for those guardrails in condition A in Year 1.

This rate is then multiplied by the 90% that is in Condition A and multiplied by the property damage only cost of \$11,900, then this is added to the crash rate multiplied by the 10% in condition A that is in poor condition and multiplied by the fatality cost of \$6,128,000. Figure 5.16 shows the Crash Cost for Scenario 3a (Delayed Maintenance by 1 year) for each condition through the 10-year analysis.

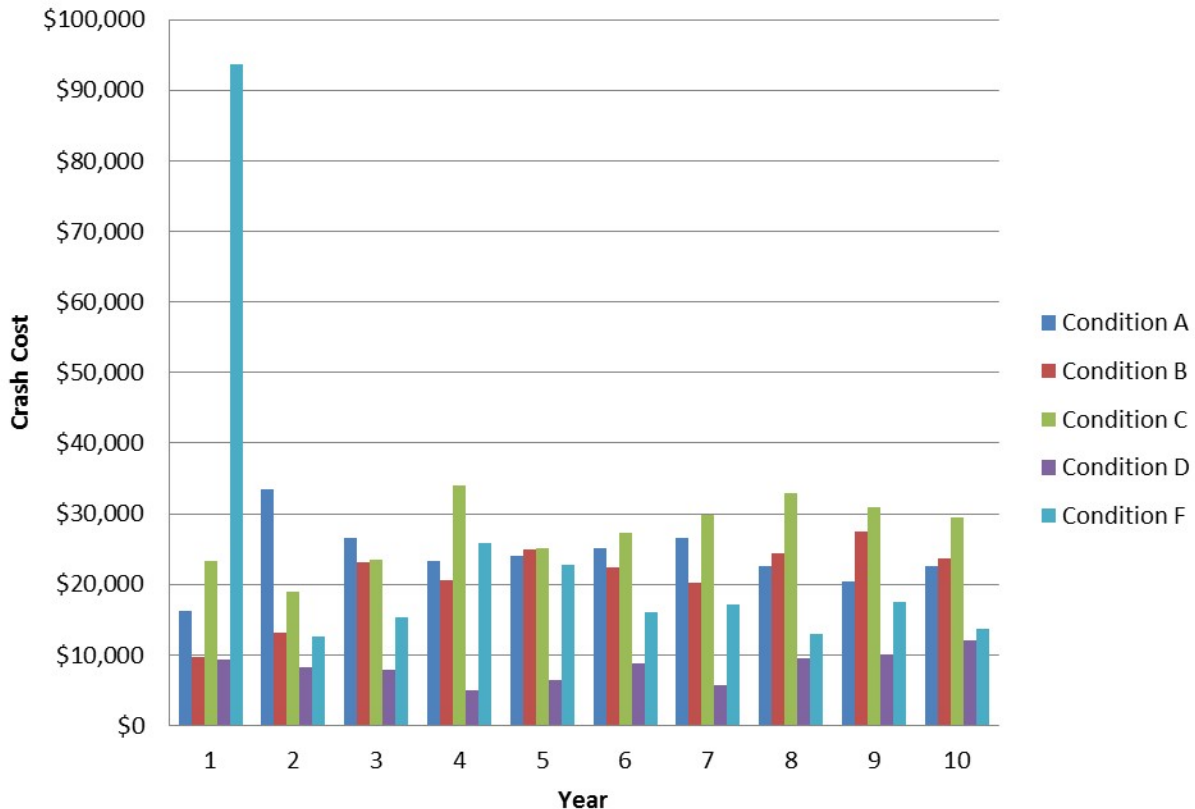


Figure 5.16: Scenario 3a Crash Cost Results

The same process was used for the Scenarios used in the Condition-Based Model. To highlight on the Crash cost differences, the Crash Cost results for Scenario 1 (All Needs) are provided in Figure 5.17.

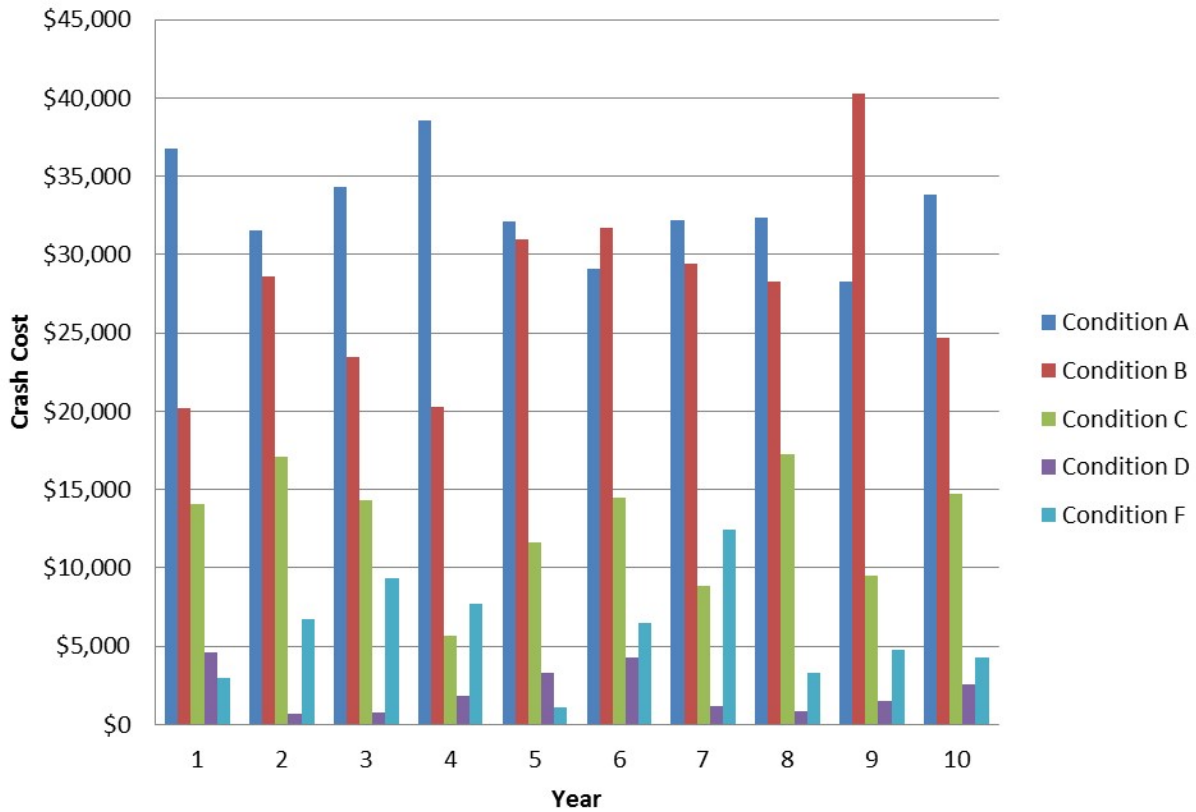


Figure 5.17: Scenario 1 Crash Cost Results

With these results and with further research, a correlation between the condition and the probability of a fatal crash could be justified. This is to say that as the guardrail condition increases the higher the probability of a fatal crash, therefore, proper maintenance of the guardrail system is imperative. As the guardrail condition improves then it is less likely that a crash will occur within the guardrail that has poor condition.

The assumptions made in utilizing the preliminary crash cost model are attributed to the inability to use the crash data provided by UDOT. The reason for this was because there were only 7 guardrail data sets that were matched between the general guardrail data and the crash cost data.



## **Chapter 6: Conclusion**

The guardrail Condition-Based Model provides agency costs, unfunded backlogged costs, guardrail network condition percentages at the beginning and the end of the analysis period, the system value, and the guardrail sustainability ratio. These results can be used by agencies to facilitate the development of a guardrail preservation program. A case study utilizing very limited data was presented to show how the model can be used in an existing asset management system to facilitate the formulation of preservation programs for guardrails at the strategic level. In the case study, results showed significant impacts produced by delayed maintenance and replacement activities and funding constraints.

It is important to estimate budget needs and assess the consequences of maintenance on the future condition and agency costs. In order to implement a proactive preservation policy, analytical tools with these capabilities are required. However, the lack of consistent data affects the development of Condition-Based Models that are required to determine key parameters such as deterioration rates, service life, crash frequencies and severity of damage. The Condition-Based Model described in this thesis is an attempt to address this problem using condition deterioration and improvement transition matrices developed from the inventory of a guardrail system.

Six scenarios were analyzed in the case study and the results show differences in agency costs and guardrail section condition over a period of 10 years. To preserve the guardrail in a good and reliable condition, a total investment of \$30M is required. If the agencies do not invest in maintenance and replacement activities, the whole guardrail network will be completely unreliable after seven years, and the agency costs will be \$290M to reestablish the functionality of the guardrail system. Scenarios 3a and 3b show the impact of postponing maintenance activities for one and three years respectively and result in about 50% increase in the total agency costs when compared to Scenario 1. Scenarios 4a and 4b correspond to budget constraint

maintenance programs that result in \$75M and \$130M backlog costs, and more than 30% and 43% of the guardrail network in Condition F.

It is recommended to integrate the Guardrail Asset Management Framework and Condition-Based Model into an overall asset management system to facilitate the formulation of highway preservation programs for guardrails at the strategic level. This can be achieved by first incorporating it into the strategic asset management level and incorporating at the network level. Both the strategic and the network level have to be committed to incorporating the guardrail asset management tools or into modifying their current process to utilize the tools. The key to integrating the guardrail asset management tools is to determine the guardrail system data that is currently being collected and determining what other information needs to be collected. Within asset management, it needs to be understood that the data needs to be consistently collected over a period of time.

## **6.1 CHALLENGES**

The implementation of asset management practices requires data and condition-based tools to predict the performance of highway assets over time. One of the major limitations that were realized in the development of the model was the lack of consistent historical inventory. The limited available inventory can be attributed to the fact that maintenance activities for guardrails are mainly reactive. Most guardrail replacements are carried out when the guardrail is severely damaged by a car crash. The Condition-Based Model is presented in this thesis along with a methodology at the strategic asset management level to estimate budget needs and the impact on the guardrail condition under different scenarios.

Connecticut DOT presented “Issues and Opportunities in Developing Highway and Transit Asset Management Plans: Connecticut DOT’s Experience,” at the 96<sup>th</sup> Annual Transportation Research Board (TRB). Connecticut DOT’s (CTDOT) research shows that current challenges include determining the inventory that has been collected and how to handle outliers within their inventory. CTDOT is also dealing with the various maturity levels within

collected inventory for different assets. These are challenges that CTDOT has been dealing with as they continue to develop their highway asset management plan and have impacted CTDOT's ability to further their asset management plan across many assets. Through these challenges, CTDOT has had setbacks in incorporating different assets into their asset management plan due to the low confidence level in analyzing the life cycle data.

CTDOT initiated their TAMP startup in April 2015 and planned to implement the TAMP in December 2016. As seen in many states, CTDOT TAMPs are currently focused on pavements, bridges, sign supports, signals, signs, and pavement markings. Guardrails are to be included in a future TAMP. The TAMP's primary goals are to keep asset inventories updated while incorporating data integration.

## **6.2 FRAMEWORK IMPLEMENTATION**

The proposed guardrail asset management support tools can be used by agencies to develop a guardrail asset management program, or for agencies that would like to further the development of their guardrail asset management program. The asset management support tools are bases for guardrail asset management programs because it utilizes data that is currently being collected, and information that is being considered in existing asset management programs. The proposed guardrail asset management support tools were developed with a primary goal, which was to use information provided through the Literature Review and information collected from agencies. The information background information was incorporated into the tools as the foundation in developing the support tools. This led to having a connection between what is being proposed in the support tools and to the practices that are already being followed in guardrail asset management.

Agencies should focus on collecting data, analyzing the data, and managing the guardrail that is within their responsibility. The framework should be utilized by agencies that want to and are able to implement guardrail asset management. In utilizing the framework, the agency

should be able to collect the guardrail location, guardrail length, and guardrail deficient length and also be able to determine maintenance and repair costs.

Also, agencies utilizing the Condition-Based Model should only expect the forecasting reports associated with the framework. One limitation is that the Scenarios within the model do not provide service life, or the location of guardrails requiring repair and maintenance. This tool is to be used for budgeting purposes.

The Condition-Based Model can be used at the strategic level to enable decision makers to have more data available when developing their preservation programs. The case study and the results show how the model can be applied to analyze the impact of different maintenance scenarios in the guardrail system condition and agency costs. The results of scenario analyses can be used at the strategic level to estimate budget needs and the impact on the guardrail system condition under different maintenance scenarios.

Through the available GIS capabilities, discussed in Section 2.8.1, agencies that have the resources to incorporate GIS into their guardrail asset management programs are advised to do so. GIS is a tool that can be used to view and analyze information across many assets and databases available. Powerful search and filter queries help with analyzing the information generated by the databases. In general, it is recommended that further evaluation be conducted towards the available GIS capabilities within the agency for proper integration for guardrail asset management practices and programs.

### **6.3 FUTURE RESEARCH**

- a. Crash documentation should be considered for future research. This would require crash documentation when a guardrail is present. As consistent data are obtained, crash frequencies can be determined and used to see if there is a correlation between guardrail preservation and the severity of vehicular accidents involving a guardrail. Crash cost should also be documented. Both of the crash related information can assist agencies in

seeing a pattern in the frequency of vehicular accidents involving guardrails. CRIS and CTCDR are crash data tools and are briefly described below.

The Texas Department of Transportation (TxDOT) publishes Texas crash data in the Crash Records Information System (CRIS). The data are published annually and results from crash reports submitted by Texas law enforcement. The crash reports are submitted by law enforcement, who in the regular course of duty, “investigates a motor vehicle crash that results in injury to or the death of a person or damage to the property of any one person to the apparent extent of \$1,000 or more...” (TxDOT, 2017). The reports are submitted no later than the 10<sup>th</sup> day from the day that the crash took place. TxDOT retains the crash data for 10 years. CRIS uses queries that help the user filter the data to compile searchable data. CRIS also allows the user to create different queries to better help the user in filtering out the data that are needed.

The Connecticut Crash Data Repository (CTCDR) is similar TxDOT CRIS. CTCDR is a tool designed to provide crash information collected by state and local law enforcement. The data provide “timely, accurate, complete and uniform crash data” (UCONN, 2017). CTCDR utilizes queries that can be used to view information on a specific data, route, route class, collision type, and severity. CTCDR also allows the user to define categories to develop and identify trends in the crash data.

- b. Consistent yearly data were not available for the case study, for further research, it is recommended that the transition matrix be developed using long-term inventoried data. With the use of consecutive yearly data, probabilities can be produced to better model the existing guardrail network and utilized for the transition matrix for the model. As more data are being collected, the agencies will be able to improve the reliability of the Condition Transition Matrix or can also use the data to develop more sophisticated models. With focusing on the Condition-Based Model, the Condition Transition Matrix would benefit from more data because the consistency of the collected data will most likely improve the accuracy of the development of the Condition Transition Matrix.

- c. While utilizing the Condition-Based Model, it is highly recommended that the inventory includes roadway classification including principal arterial, minor arterial, collector, local, urban, and rural classifications. This can assist agencies in reviewing results for each roadway classification and determine if a particular roadway classification requires the most funding allocation and resources. Also, documentation of the purpose for the guardrail placement at the locations such as to shield the motorist from an embankment or provide a barrier between the motorist and a horizontal curve can assist agencies in determining the frequency that accidents or maintenance occurs at these particular locations. This may be helpful since these areas may be considered a higher priority depending on the roadway classification and reasoning. These results can help an agency determine the necessary funding allocation based on the frequency of the higher priority areas which can also be correlated to the ADT used in the Maintenance Priority Index.
- d. The lack of consistent long-term consistent data resulted in challenges which included in a limited amount of data resulting in having to make assumptions, as highlighted in Section 4.3. It is imperative that the guardrail asset management tools that are presented in this thesis be further analyzed with quality data collected each year. Through further research, the use of the @Risk software is recommended to perform risk analysis using Monte Carlo simulation which utilizes probabilities to determine outcomes that best model real life trends.
- e. More research is required to determine any variation that would be necessary to apply the methodology presented in the Guardrail Asset Management Framework to other guardrail types. Any variations may result from the differences in the service life, material and other factors.

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## **Vita**

Sandra Gutierrez earned her Bachelors of Science in Civil Engineering in spring 2014 from the University of Texas at El Paso (UTEP). During her undergraduate studies, she participated in a Network for Earthquake Engineering Simulation Research Experiences for Undergraduates (NEES REU) at The University of California, San Diego under the supervision of Dr. John Van de Lindt. She assisted with instrumentation set-up and data analysis to validate retrofit techniques for a four-story soft-story wood frame structure. During her last year of undergraduate studies, she assisted GRV Integrated Engineering Solutions. Sandra provided GRV with assistance for the installation of traffic counting systems on roadways, and with recording traffic travel times between intersections for multiple corridors, under the supervision of Marvin Gomez. She soon received the National Science Foundation (NSF) Scholarship for the Graduate Bridge Program for Highly Achieving Engineering and Computer Science Students and continued to further her education by pursuing a Master's of Science in Civil Engineering with a focus in Transportation Engineering/Infrastructure Management starting in Fall 2014. While pursuing her master's degree, she began working part-time at Parkhill Smith and Cooper, Inc., in January 2015, and was given the opportunity to work full-time a year later in the Transportation Sector, under the supervision of Eduardo Hernandez and Kyle Jackson. She plans to continue practicing engineering and become a Professional Engineer in her field.

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