RESEARCH

UDOT

Keeping Utah Moving

Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

Report No. UT-22.03

INCORPORATING MAINTENANCE COSTS AND CONSIDERATIONS INTO HIGHWAY DESIGN DECISIONS

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Final Report
January 2022

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) and the Mountain-Plains Consortium (MPC) University Transportation Center for funding this research, and the following individuals from UDOT for their role providing feedback and their service on the Technical Advisory Committee:

- Kevin Nichol, Project Manager, UDOT Research and Innovation Division
- David Eixenberger, Former UDOT Project Manager and Consultant
- W. Scott Jones, Former UDOT Maintenance Engineer, now Director of Data, Technology, & Analytics
- Kevin Griffin, Former UDOT Director of Maintenance
- Fred Doehring, UDOT Deputy Director for Pre-Construction
- Katie Powell, Consultant Project Manager

TECHNICAL REPORT ABSTRACT

1. Report No. UT-22.03	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle INCORPORATING MAINTENANCE COSTS AND CONSIDERATIONS INTO HIGHWAY DESIGN DECISIONS		5. Report Date January 2022 6. Performing Organization Code
7. Author(s) Juan C. Medina, Jeffrey Taylor (Phase II); Richard J. Porter, Milan T. Zlatkovic, Anusha Musunuru (Phase I)		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Utah Department of Civil and Environmental Engineering 110 S. Central Campus Drive, Suite 2000 Salt Lake City, UT 84112		10. Work Unit No. 5H086 10H 11. Contract or Grant No. 15-8669
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Final Apr 2015 to Jan 2022 14. Sponsoring Agency Code UT14.203

15. Supplementary Notes

This study was also sponsored by the Mountain-Plains Consortium UTC, supported by Federal Highway Administration through project MPC-493.

16. Abstract

Maintenance costs, while significant throughout the life-cycle of a project, may sometimes not receive full consideration as inputs to design decisions. In Phase I, this project identified research priorities in coordination with the Technical Advisory Committee (TAC) after recommendations were formulated based on reviews of published literature, design policies, and practice, as well as on a survey of design and maintenance personnel. As a result, four potential topics for further exploration, including maintenance and long-term costs for barriers, drainage, cross-section elements and temporary control, and intersections/interchange form and design emerged. Discussions with the TAC steered the conversation toward an initial big picture analysis of barrier systems and related costs extracted from the databases of different DOTs.

In Phase II, the research team accessed 10 years of detailed barrier-related work order data and transactional expenses from internal tracking and accounting systems. After data post-processing using custom search keys for free text fields and comparing different data sources, initial costs, maintenance costs, and project-related costs were extracted by barrier type. Work associated to barrier damage caused by vehicle crashes were available and quantified, but only for cable barriers due to limitations in reporting information in both the work orders and accounting transactions. Adjustments for inflation using consumer price indices were applied to all costs for the analysis period, and a life cycle cost analysis (LCAA) framework was illustrated for main barrier types.

Expenses for different barrier types, including initial costs, maintenance, and other project costs will be valuable to characterize differences in the long-term costs of different barrier systems, particularly for the more specific items in the barrier subcategories (for initial costs and other project costs). Also, unitary costs of crash-related expenses for cable barriers, as a function of posts damaged and expected frequency of such damages by vehicle type, could help illustrate future LCCA examples.

Difficulties with the data processing, and in general for future analysis of maintenance costs, stemmed from the use of non-standardized and/or optional fields in expense reports to characterize the nature of some of the work performed. Alternative items in the priority list could be further explored using similar financial system reports. However, similar pitfalls would be encountered at finer levels of detail, when specific assets subject to maintenance work need to be identified. This is expected to apply to drainage elements, cross-section elements and temporary traffic control, and intersection and interchange form and design. Recommendations to improve maintenance data collection for tracking and cost evaluations are provided.

17. Key Words Maintenance expenses, design practices, asset cost evaluation, long-term road barrier system, cable barrier, concrete barrier, guardrail, attenuator and crash cushion, recoverable crash repair.		18. Distribution Statement Not restricted. Available through: UDOT Research Division 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal N/A
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 142	22. Price N/A	

TABLE OF CONTENTS

INTRODUCTION

The strategic plan of the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Design includes goals related to incorporating costs and impacts associated with maintenance activities into design decisions. These goals include: 1) develop cost-effective solutions for delivering projects that minimize the operational and maintenance resources needed to sustain system effectiveness and functionality; and 2) support efforts to enhance the involvement of construction, maintenance, and operations personnel in the design phase of project delivery.

Maintenance costs, while significant throughout the life-cycle of a project, may sometimes not receive full consideration as inputs to design decisions. Important factors may include the frequency and intensity of routine maintenance activities associated with highway and street features and materials, as well as the selection of physical highway and street dimensions to support all types of future maintenance activities and associated temporary traffic control. Maintenance needs of bridges, pavement, and drainage infrastructure are large budget items influenced by initial design decisions. In terms of roadway geometric features, maintenance costs and considerations may be particularly relevant to decisions related to cross section allocation, roundabouts, intersection channelization, curb returns, raised medians, indirect left-turn and U-turn treatments, vertical clearance, and pedestrian/bicyclist accommodation. Roadside features such as barriers, sidewalks, signal supports, lighting, signs, and any related ADA characteristics associated with these features also have significant maintenance needs. This ongoing research project will examine possible policies, procedures, and practices for effectively including life-cycle maintenance costs and other maintenance considerations into highway design decisions.

The main objectives addressed in this research are the following: 1) identify how transportation system- and project-level design decisions impact long-term maintenance costs and operations through a life-cycle cost analysis of selected item categories, and 2) analyze costs trends over time to recommend possible changes to practices that minimize maintenance costs and optimize maintenance operations.

The execution of this project was divided into two phases. Phase I was an exploratory effort where the research team, in coordination with the Technical Advisory Committee (TAC), identified common issues that had potential to be addressed through a more focused analysis in Phase II. A synthesis of the literature on design decisions and their relation to expected performance and resulting costs was initially conducted to identify items for further exploration. The literature review was accompanied by a survey submitted to multiple transportation agencies covering questions on maintenance considerations and design decisions. Phase I elaborated on the combined available information to produce a number of candidate topics that were discussed with the TAC for prioritization into Phase II. Out of an initial set of seven candidate topics, the following four were recommended for further consideration: 1) barrier type, 2) drainage, 3) cross-section elements and temporary traffic control, and 4) intersection and interchange form and design.

In Phase II, priorities were further discussed with the TAC, resulting in the main focus of efforts being directed toward topics with more potential for quantitative analysis, barrier systems being the main area of interest. The research team accessed 10 years of detailed barrier-related work order data and transactional expenses from internal tracking and accounting systems.

Expenses for different barrier types, including initial costs, maintenance, other project costs, and crash-related costs were extracted and adjusted for inflation, and are expected to be valuable to characterize differences in the long-term costs of different barrier systems, particularly for the more specific items in the barrier subcategories (for initial costs and other project costs).

Difficulties with the data processing, and in general, for future analysis of maintenance costs, stemmed from the use of non-standardized and/or optional fields in expense reports to characterize the nature of some of the work performed. Alternative items in the priority list could be further explored using similar financial system reports. However, similar pitfalls would be encountered at fine levels of detail, when specific assets subject to maintenance work need to be identified. This is expected to apply to drainage elements, cross-section elements and temporary traffic control, and intersection and interchange form and design.

This report is organized as follows. First, initial documentation of past research, design policies, and practice (including a survey) from Phase I are included in the initial sections, followed by a description of the data collection and analysis conducted in Phase II for barrier systems. Conclusions and recommendations to improve maintenance data collection for cost tracking and evaluation are provided comprise the main body of the report. Finally, additional information including the survey questionnaire, survey responses, and detailed costs for extended subgroups of barrier types are also added in the appendices.

PHASE I

REVIEW OF LITERATURE

A review of published literature uncovered documented research needs that were consistent with the intent of this research project to explore ways to effectively include life-cycle maintenance costs and other maintenance considerations into highway design decisions. However, supporting details were relatively scarce. Generally speaking, the related literature noted that highway and street design is frequently thought of as a series of activities and decisions that involve identifying design controls and applying design criteria, executing technical calculations and analysis, providing technical descriptions of design alternatives, and estimating quantities associated with design alternatives. However, assumptions and projections regarding expected performance outcomes, expected life, maintenance requirements, and the associated agency and societal costs corresponding to design alternatives are equally important (Ceran & Newman, 1992) (Karim, 2011). Inadequate consideration of maintenance needs and corresponding maintenance activities during highway and street design has the potential effect of contributing to unexpected and significant levels of future maintenance activities and agency costs, as well as to inconvenient impacts on highway users (Ceran & Newman, 1992).

Five general reasons for not fully considering maintenance aspects and activities during highway planning and design processes were provided by one published study (Karim, 2011):

1) limited resources in the maintenance division of an agency for devoting time and staff to reviews and possible revisions of construction documents;

2) limited design budgets for a project that do not support full consideration of all life-cycle costs during the design stage;

3) aesthetic requirements for the design of roadways, even when designers and other decision-makers are aware of the higher future maintenance costs associated with more aesthetic alternatives;

4) lack of designer experience in identifying possible roadway maintenance challenges; and

5) inadequate interactions between highway designers and maintenance personnel during the planning and design stages of projects.

With aging highway facilities and more limited resources, Ceran & Newman (1992) noted a significant need to specifically identify and communicate potential maintenance problems and issues that can be addressed through improved design practices (Ceran & Newman, 1992).

The following sections of this literature review summarize topics relevant to the objectives of this research project. Brief overviews of value engineering and life-cycle cost analysis are first provided, as these concepts are expected to remain relevant throughout this research effort. Published research on maintenance considerations in highway and street design is then summarized. The summary will show that work in this area is fairly limited. Finally, a brief summary of maintenance considerations in building design is included to determine whether ideas transferable to highway and street design are readily available in this context. The section concludes with a summary of key literature review findings.

Overview of Value Engineering

Value Engineering (VE) is the systematic review of a project, product, or process to improve performance, quality, and/or life-cycle cost by an independent multidisciplinary team of specialists, who are not directly involved with the project and/or process (Wilson, 2005). The specialist team identifies the function of the project, establishes a worth for that function, and generates alternatives through the use of creative thinking. It also provides the needed functions and reliability, at the lowest overall cost (Wilson, 2005) (Berry, 2013) (FHWA, 2014). The VE process is unique in the sense that it incorporates longer-term values of the project: design, construction, maintenance, contractor, federal, state, and local approval agencies, and other stakeholders.

In the United States, VE, sometimes called the value methodology (VM), has been used to improve transportation projects for more than 60 years (Parker, 1977). However, highway projects were not extensively studied using VE methodologies until 1985. Up to that time, VE had not been generally applied to highway projects due to tight schedules and the concern about designers' reactions (Turner & Reark, 1981). However, since 1993, federal agencies and STAs have been using VE "as a management tool, where appropriate, to ensure realistic budgets, identify and remove nonessential capital and operating costs, and improve and maintain optimum quality of program and acquisition functions" (FFC, 2001). A typical VE study is conducted over a period that may vary depending on the size of the project, and generally consists of the phases summarized in **Error! Reference source not found.**.

In early 1997, the Federal Highway Administration (FHWA) first published a VE regulation that would require states to carry out a VE analysis for all federal-aid funded highway projects with an estimated total cost of $25 million or more (Berry, 2013). In 2014, the VE requirements were changed under the Moving Ahead for Progress in the 21st Century (MAP-21) act, and the VE final rule was published by FHWA in September, 2014. The changes to the regulation that were recommended were (FHWA, 2014):

- Increased the project size thresholds requiring VE analysis to:

  - Projects on the National Highway System (NHS) receiving federal assistance with an estimated total cost of $50 million or more; or

  - Bridge projects on the NHS receiving federal assistance with an estimated total cost of $40 million or more;

- Removed the VE analysis requirement for projects delivered using the design/build method of construction; and

- Provided VE analysis guidance for projects delivered using the construction manager/general contractor (CM/GC) method of project delivery.

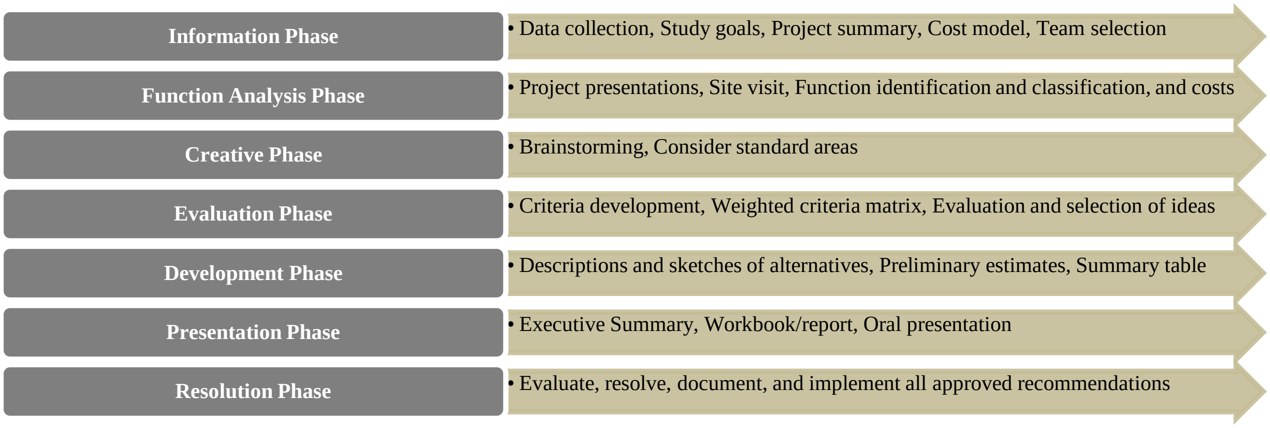


Figure 1. Value Engineering Job Plan (adopted from (Berry, 2013); (Clark, 1999))

FHWA monitors the application of VE on federal-aid projects throughout the United States and produces annual summary reports (FHWA, 2015). These reports are available from the year the VE regulation was first introduced (1997) until recently (2013). Figure summarizes the number of VE studies documented at the estimated return on investment (ROI) for the 5-year period from 2009 to 2013. On average, 368 federal-aid VE studies were performed annually within the years 2009 and 2013. The ROI values ranged from a minimum of 80:1 in the year 2011 to a maximum of 146:1 in the year 2010. Value engineering creates an environment where the project team finds creative solutions to complex problems with improved quality, effective use of the resources, and high return on investment (Services, 2015).

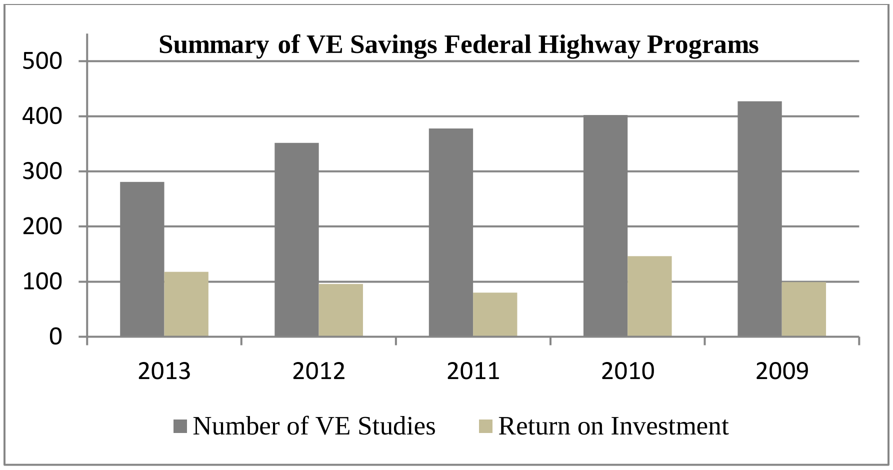


Figure 2. Summary of VE Savings Federal Highway Programs (FHWA, 2014)

Overview of Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the overall, long-term economic efficiency of competing alternative transportation investment options (Walls III & Smith, 1998) (FHWA, 2002). In short, LCCA is a process of evaluating the economic performance of a transportation project over its entire life. It combines the initial monetary investment with other estimated relevant costs and expenses associated with maintenance and operations over the life of the alternative. It attempts to identify the most effective overall design that is associated with the lowest long-term costs and that satisfies the performance objectives being sought for the transportation investment (Walls III & Smith, 1998) (University, 2005).

Given the defined limitations on resources for transportation projects, it is more essential for federal and state transportation agencies and leaders to prioritize and target available funds toward projects with the greatest economic benefits and lower long-term costs (ASCE & Eno, 2014) (Doctor, 2014). LCCA analysis is particularly useful in this context in the sense that it looks at the initial costs for design and construction of a project, combined with the long-term costs associated with maintenance, operations, and the retiring of a project. The ability of the resulting transportation asset of a project to provide service over time is predicated on its being maintained appropriately by the agency. Thus, investment decisions should consider not only the initial activity that creates a public good, but also all future activities that will be required to keep that investment available to the public (FHWA, 2002). As part of ongoing NCHRP project 14-20A, processes are being developed to more fully understand the consequences of delayed application of maintenance treatments on highway pavements, bridges, and other physical assets. Consequences are being quantified in terms of various performance indicators, cost to owners and road users, and other relevant factors.

A general LCCA methodology for pavement design is outlined below in Figure . (Walls III & Smith, 1998) (FHWA, 2002). The steps are ordered so that the analysis builds upon information gathered in prior steps. This analysis can be performed with manual calculations or by using recommended software, such as FHWA's *RealCost* software for pavement design (Greenroads, 2015). The same methodology can be applied to other aspects of each alternative in transportation projects, and can also include steps for monetizing the quality of user service or utility for a specific, given volume of traffic to yield a more comprehensive set of results. For the analysis and calculations, the initial values used should be consistent with any existing owner agency policies or default inputs, engineering estimates, and/or representative, historic data. If no standard agency policy exists, LCCA tools, such as *RealCost* for pavement design, provide default values for users to consider. Tools also have options to report probabilistic values (considering the realistic uncertainty in cost estimates) as well as deterministic results (Greenroads, 2015).

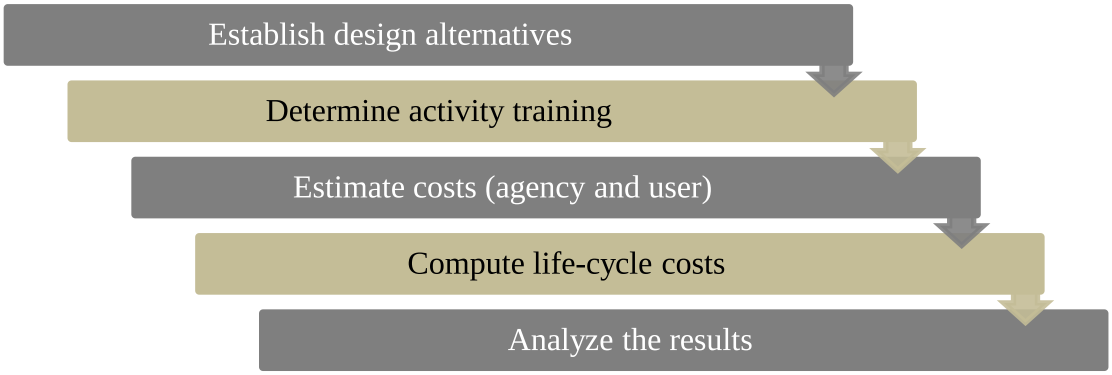


Figure 3. Example process of LCCA Methodology (FHWA, 2002)

Life-cycle costs for road assets are instrumental in selecting road designs or evaluating bids (Adams & Kang, 2006) (Stenbeck, 2004). In the calculation of life-cycle costs for a road design, both road agency costs and socio-economic costs (also known as user costs) should be included (Karim, 2011) (Greenroads, 2015). A cost-benefit analysis generally includes the components specified below. Assumptions used for agency costs and socio-economic costs should be consistent in each analysis for projects with multiple major features (Greenroads, 2015).

Agency Costs: Costs from the planning, design, construction, operation, maintenance, and rehabilitation of a project (Karim, 2011) (Greenroads, 2015).

Preliminary Engineering	Planning and design costs
Contract Administration	Bidding and contract oversight
Initial Construction	Costs incurred during the initial construction
Construction Supervision	Construction management and inspections
Maintenance	Basic maintenance activities associated with the assets
Rehabilitation	Costs to maintain, rehabilitate, or retrofit an asset throughout its service life
Administrative Costs	Cost of pavement management and other administrative costs
Salvage Value	Expected value of materials and equipment at the end of service life

Socio-Economic Costs: Costs to road users who use the facility during normal operation and during construction and maintenance periods (Karim, 2011) (Greenroads, 2015).

Road User Costs	Vehicle operating costs, and costs for the time people spend on the road
Crash Costs	Costs incurred by crashes on the roadway
Work Zone Costs	Costs incurred by the user from work zone delays
Environmental Costs	Costs incurred from impacts to the environment

FHWA has been promoting the use of LCCA for transportation investment decisions since the Intermodal Surface Transportation Equity Act of 1991 (FHWA, 2002) (ASCE & Eno, 2014). Most state agencies use LCCA in their pavement design process, but implementation beyond this use varies widely (Rangaraju & et. al., 2014). One study showed that, while 94 percent of the survey respondent states used LCCA for pavement design and analysis, the application beyond pavements was less extensive and the range of parameters used was not consistent among the state agencies (Rangaraju & et. al., 2014). LCCA is often performed at the preliminary engineering and planning phases of a project and relies on accurately predicting future costs, which can sometimes be challenging at earlier project development stages (ASCE & Eno, 2014).

An interim technical bulletin released from the FHWA provides a more detailed discussion of this methodology and its components, particularly with regard to the user cost calculations, discount rates applied, and the treatment of uncertainty in the analysis for LCCA in pavement design (Walls III & Smith, 1998). However, it is important to note that the *RealCost* software is not required to perform the analysis and calculations in LCCA, as any method that conforms to FHWA's interim technical bulletin for pavements (Walls III & Smith, 1998) can be used for LCCA computation.

Potential Issues

Several challenges and potential issues associated with LCCA have been identified in the literature (ASCE & Eno, 2014) (Greenroads, 2015):

- LCCA is a fairly standard economic analysis tool, used in the selection of alternatives that impact both current and future costs. In the estimation of the costs for alternatives over their service life, there is a higher chance to input incorrect or irrelevant numbers and misuse the results obtained from the analysis. Hence, users should be familiar with the details of the analysis and any related software they are using before actually conducting an LCCA.

- The meaningfulness of LCCA outputs relies heavily on good estimates of future performance life, agency costs, and socio-economic costs. All of these rely on well-informed engineering judgment and past history rather than economic theory or principles.

- LCCA should be done during the earliest possible project development stages where it would be most likely to influence project decisions. However, more limited project data is available at these earlier stages. More project data is available to inform LCCA in the later stages of a project, but the usefulness of the analysis to impact project concepts and directions has decreased significantly by that point.

Regardless of the limitations, LCCA provides a deeper understanding of the benefits and costs over the complete life-cycle or service life of an asset to more fully inform decision makers and help target limited funds to the most beneficial and cost-effective projects (ASCE & Eno, 2014).

Maintenance Considerations in Highway and Street Design

Current highway and street design practices do not always explicitly consider future maintenance needs associated with various design alternatives, even though projects that are difficult or costly to maintain, or those that require frequent maintenance activities, are considered to be “poorly designed” (TXDOT, 2014). The need to specifically identify and communicate maintenance problems that can be addressed through better design is increasing as design practice continues toward more “performance-based” and “practical” decision-making (Ceran & Newman, 1992) (Prarche, 2007). This view is consistent with earlier stated AASHTO goals to develop cost-effective solutions for delivering projects that minimize the operational and maintenance resources needed to sustain system effectiveness and functionality, and support efforts to enhance the involvement of construction, maintenance, and operations personnel in the design phase of project delivery.

The cost of a road or highway project over its service life is, among other things, a function of design standards, construction quality control, maintenance strategies, and maintenance quality (Karim, 2011). All of these aspects control the rate of road deterioration and dictate the maintenance workload throughout the life-cycle of a road. This concept was illustrated by Freer-Hewish (1986), as shown in Figure . Increases in the required maintenance workload has an effect on road user costs, which is represented in Figure as vehicle operation costs.

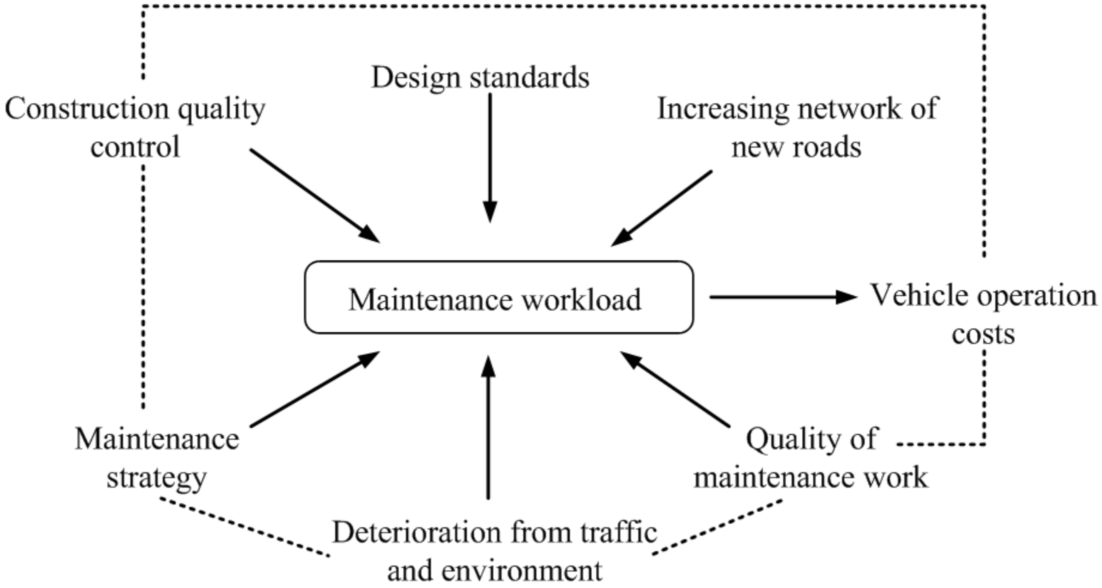


Figure 4. Development of Maintenance Workload (Freer-Hewish, 1986)

Two major factors contributing to the higher maintenance costs for highways were identified by (Karim, 2011) as: 1) insufficient consideration of maintenance aspects during design, and 2) inadequate support for designers to more fully consider maintenance during the concept development and design phases of project development. The following associated improvements were suggested by (Thorsman & Magnusson, 2004) and (Karim, 2011):

- Improving methods and technologies for reducing user costs of maintenance through a reduction in intervention time and use of efficient tools;
- Creating functions for supporting designers in coordinating maintenance-related consulting between involved parties; and
- Improving coordination and information sharing between contractors.

National Cooperative Highway Research Program (NCHRP) Report 349 by Ceran & Newman (1992) recommended a set of procedures for explicitly recognizing the maintenance implications of design, and a series of suggested improvements in design details intended to alleviate maintenance problems. These recommendations were based on a research approach that involved a literature search, surveys of practices in transportation agencies, interviews, and a pilot test within the Utah Department of Transportation. A checklist concerning possible improvements to design features that accommodate maintenance concerns was also provided in the report. The majority of findings in the report linked the insufficient consideration of maintenance aspects in design to the lack of communication between designers and maintenance personnel during the project scoping and design phases of projects.

Ceran & Newman (1992) noted that it is important to begin maintenance consideration early, during corridor location studies, and continue these considerations all the way through design. Design-related practices and activities with the most significant opportunities to effectively incorporate future maintenance needs of a facility were identified, and included (Ceran & Newman, 1992):

1. Investigating geology and geotechnical features to avoid or minimize potential problems (rock slides, highly erosive soils, unsuitable materials, and similar).
2. Maximizing southern exposure in mountainous and hilly areas to minimize snow and ice accumulation.
3. Allowing space with proper drainage for dumping or storing plowed snow.
4. Giving careful attention to adequate drainage needs and protection from flooding, since the maintenance of drainage elements is a major cost item.
5. Considering access requirements for maintenance and rehabilitation in all aspects of highway location and design.
6. Avoiding too many horizontal curves, which can require more maintenance due to runoff from melting snow and ice, and carefully considering sag vertical curve designs to avoid water retention.
7. Considering maintenance needs when establishing right-of-way (ROW) limits and fence locations. This may include purchasing additional ROW to flatten short sections of high embankments so that they can be maintained more easily.
8. Conducting a value engineering analysis that includes maintenance costs and considerations in the analysis to compare embankment sections having flat slopes and wider ROW with sections having steeper slopes, retaining walls, or both.
9. Considering maintenance facility requirements associated with maintenance needs (yards, pit sites, snow storage, waste areas, and similar).

Specific recommendations were provided by the NCHRP Report 349 authors for different facility components, defined by the authors as: 1) cross-section elements and pavements, 2) drainage systems, and 3) appurtenances. A brief summary of these recommendations for each facility component is provided in the following sub-sections.

Cross-section elements and Pavements

Recommendations associated with cross-section elements and pavements covered mainline and ramp pavements, shoulders, medians, islands, and embankments. Since pavement maintenance and rehabilitation make up a significant portion of maintenance expenditures, pavements were represented at a significant level in the following maintenance considerations that were identified:

1. Provide adequate subgrade drainage, minimize loss of fine material and clogging of the sub-drainage by wrapping filter fabrics around French drains or underdrain pipes, and outlet drain pipes into paved ditches or culverts.

2. Provide skid-resistant surfacing in wet climates.

3. Consider future pavement resurfacing requirements when establishing vertical clearances and designing elements such as inlet grates and manhole covers.

4. Consider the use of longer pavement life and PCC pavement in congested urban areas to reduce the need for rehabilitation and the costs associated with it.

5. Consider the use of full pavement design from shoulder to shoulder in urban areas and omit troublesome joints between pavement and shoulders. Full pavement design is an expensive solution and should only be used in heavily traveled urban highways. Other roads should consider extending the full pavement structure at least two to three feet into the shoulder.

6. Consider paving area under guardrails to minimize vegetation control problems.

7. Provide a shoulder sloping away from the pavement on the high side of superelevated cross sections to prevent icing conditions on pavement due to melting snow that is deposited on the high shoulder.

8. Create a contrast between asphalt pavement and asphalt shoulder by applying stone chips to the shoulder surface. A slotted pipe can be used to help prevent clogging from loose stones.

9. Avoid the use of unpaved, narrow medians or small traffic islands. Maintaining narrow grassy areas is difficult and costly.

10. Consider offsetting concrete barriers (if median is 22 feet or less) to increase shoulders and allow parking of maintenance vehicles.
11. Provide flat roadside slopes and rounding to minimize erosion potential and to make maintenance operations easier.
12. Consider providing benches in higher cut slopes to collect debris, slow runoff, and collect water from slope pipes. Access for maintenance vehicles should be provided.

Drainage Systems

Maintenance of drainage systems is costly. For that reason, NCHRP Report 349 noted that attention during design should be given to future considerations such as controlling erosion in ditches, cleaning culverts and storm water systems, repairing eroded and scoured outlet areas, controlling corrosion, and repairing damage to drainage systems due to frost and clogging. In planning drainage systems, Ceran & Newman (1992) recommended that designers consider the following strategies related to minimizing maintenance costs associated with drainage infrastructure:

1. Select horizontal and vertical culvert alignments so that inlets and outlets are close to existing channels, therefore preventing sediment or erosion.
2. Base the selection of pipe and culvert materials on evaluations of acidity, resistivity, chloride, and sulfate levels in the soil and water. Abrasion of culverts will depend on the flow characteristics and materials carried by the stream.
3. Size culverts to allow passage of debris and provide access for maintenance equipment to support periodic cleaning.
4. Provide a full or partial headwall to anchor pipe subject to uplift due to scouring and buoyancy, and provide energy dissipaters at the outlets where scouring and erosion are possible. Access for maintenance at the outlet is also necessary.
5. Provide access to drainage ditches along highways where maintenance vehicles can cross easily and ditches are strong enough to support the equipment. Proper functioning of ditches is essential to convey surface water out of the highway ROW.
6. Provide appropriate ditch grades to minimize the possibility of erosion or sedimentation.
7. Provide inlets in grassed medians and in curbed sections to eliminate water retention. All inlets should be combined with curb openings if debris accumulation is a problem.

8. Avoid the use of curbs when possible to reduce safety concerns related to higher-speed traffic and damage to snow removal equipment.

Appurtenances

Appurtenances were classified by Ceran & Newman (1992) into two main categories: 1) roadway appurtenances, which included barriers, guardrails, glare screens, pavement markings, pavement markers, and rumble strips; or 2) attenuators and roadside appurtenances, which included signs, lights, delineators, sound walls, and fences. Appurtenances need to be maintained, and therefore Ceran & Newman (1992) noted that these needs should be considered early in the design and selection process in order to minimize future maintenance.

If barriers and guardrails are needed to prevent vehicles from encroaching into the roadside, the following options were recommended:

1. Use concrete median barriers in narrow medians to redirect vehicles parallel to the traveled way.

2. Consider using a concrete barrier as a combination barrier and glare screen by extending its height.

3. Consider designing a water-conveying median barrier to facilitate cleaning the catch basins under the barrier.

4. Consider the use of open guardrail design in areas subject to snow or sand accumulation.

5. Provide wider medians or lighting to eliminate the need for glare screens.

6. Use materials that are the least prone to vandalism.

Pavement markings and markers wear from traffic, snow plows, sanding, and atmospheric conditions, and therefore require constant maintenance. Many jurisdictions recommend the use of epoxy, thermoplastic material, or precut tape in place of paint. Standard paint may be cheaper initially, but it does not withstand heavy traffic and harsh weather conditions. Raised pavement markers provide good visibility and have a long lifespan in areas that do not receive snow and require snow plowing. A grooved system with recessed pavement markings can be used in snow-plow areas. In some situations, depressed rumble strips should be considered in place of raised markers.

Attenuators are used in places where potentially hazardous fixed objects cannot be avoided, such as bridge abutments, bridge rails, and sign posts. Ceran & Newman (1992) noted that an ideal attenuator is durable and can easily be brought back to its original condition and position with inexpensive and available replacement parts. They recommended considering the needs of snow removal and storage when using an attenuator, and making sure it does not create hazardous conditions on adjacent lanes immediately following a collision.

Ceran & Newman (1992) also noted that roadside appurtenances should be placed with maintenance access availability. Major maintenance requirements for signs include painting, cleaning, replacing, and servicing fixtures of lighted signs, and repairing or replacing support posts damaged by crashes or deterioration. Locating signs so that guardrail requirements are minimized, access is easily obtained, sign visibility is not inhibited, conflict with landscaping and other highway elements is avoided, and vegetation control operations are not hampered is desirable.

Lighting is intended to improve visibility at night, increasing traffic safety and user security. Maintenance requirements associated with lighting include cleaning, lamp replacement, repairs, and replacement. Sound walls and fences provide protection and improved maintenance, but both require repair or replacement due to vehicular crashes, deterioration, vandalism, and rock slides. Other roadside maintenance challenges include managing vegetation growth by mowing or chemical applications, collecting debris and litter, minimizing the adverse effects of deicing chemicals on turf and trees, controlling erosion, and repairing the results of vandalism.

The overall goal in highway design is to reduce the costs of maintenance and construction, and to obtain the maximum benefit from highway expenditures at a minimum cost over the expected life of the project. The impact of these operations on the highway user is critical, and highway maintenance processes should accommodate the ever-present effect of and on traffic. In every maintenance situation, safety and accessibility are key considerations for everyone involved.

Road Design that Fully Considers Future Maintenance

In a paper by Karim and Magnusson (2008), the authors identified obstacles that prevent sufficient consideration of future road maintenance needs during the highway planning and design phases. Through interviews and reviews of design-related documents, they identified major challenges with fully considering maintenance within the highway planning and design process related to consulting, knowledge, planning and design activities, regulations, organizational structure, and demands from other authorities. These challenges, organized in six areas, were identified during their observations and included (Karim and Magnusson, 2008):

1. *Insufficient consulting*. Consulting between personnel involved in maintenance activities and in planning and design was limited to only a few meetings. Most of those meetings were arranged during the construction phase. Any design corrections during this late phase are usually difficult and costly to realize.

2. *Insufficient knowledge*. This area captured challenges related to knowledge regarding road planning, design, and road maintenance that spans across the boundaries of these

different areas and comes from experience in each. Insufficient consideration of maintainability often resulted when project managers or consultants did not have sufficient knowledge about the costs and performance of maintenance activities.

3. *Policies without maintainability consideration*. Policies associated with planning and design were created without sufficient consideration to maintainability. As a result, road designs consistent with these policies did not cover maintainability aspects.
4. *Insufficient consideration during planning and design*. Deficiency in fully considering maintenance impacts during planning and design activities resulted in choosing road designs that required costly and unnecessary maintenance activities. In these observed cases, limited investment budgets forced project managers and consultants to select cheaper road designs, which required more costly maintenance measures.
5. *Organizational structure*. Problems identified in this area were related to the organizational structure of road authorities. A linear organization often led to poor coordination between different processes and activities of road authorities, which resulted in the poor exchange of knowledge and experience.
6. *Demands from other authorities*. During the planning and design phases, municipalities and county administrations presented arguments and requirements that were perceived as more important than maintainability, which meant that maintainability was often overlooked.

Karim and Magnusson (2008) analyzed these challenges, and on the basis of their analysis, they offered the following recommendations to eliminate insufficient consideration of maintainability aspects during planning and design activities:

1. Set up well-defined and long-term goals for maintenance along with methods to evaluate the fulfillment of these goals.
2. Develop well-structured systems for experience exchange and consultation among personnel involved in maintenance activities and personnel involved in the planning and design process.
3. Increase knowledge regarding road maintenance needs among personnel involved in planning and design.
4. Develop a systematic evaluation process with clear guidelines for examining road projects to ensure adequate consideration of maintenance as part of a quality assurance system. Completed projects could inform development of this process.

5. Add maintainability considerations to the planning and design-related guidelines, regulations, criteria, and other related documents.
6. Create guidelines and requirements for future maintenance considerations, which are explicitly incorporated into requests for quotations and other purchasing-related documents.
7. Create incentives for consultants to consider maintainability aspects during planning and design activities to a sufficient extent.

Karim and Magnusson (2008) believed that implementation of these changes would contribute to the design of roads that did not require unnecessary and costly maintenance measures, and would increase the efficiency of future maintenance activities.

Overview of Maintenance Considerations in Building Design

As part of the literature for this project, the research team explored how maintenance is considered during the design of buildings to see if any relevant ideas could be identified and transferred to the highway and street context. One paper, (Williamson & et. al., 2010) investigated techniques that can be utilized on new building projects to prevent or reduce premature and unnecessary future building maintenance. Two techniques that have proved to be effective when used during the building design process to consider future maintenance were described in detail: Value Management (VM) and Whole Life Costing (WLC).

Value Management (VM)

The method is based on the fundamental idea that best value is not about cost cutting, but about achieving the expected value or performance from project definition to delivery. Dallas (2006) stated that VM provides an effective process to maximize value, in line with owner and user requirements. VM provides a powerful way of exploring a client's needs in depth by addressing inconsistencies between a building's design and its intended uses and expressing these in a language that all parties can understand (Williamson & et. al., 2010). The research on building design contends that VM is a useful technique for reducing future maintenance costs if the right emphases are used at the outset (Williamson & et. al., 2010). To apply it to highway design projects, designers should be made aware of the implications of their decisions on whole life-cycle costs, which will include future maintenance demands. The maintenance personnel should be involved with the designer at the early stages of projects to focus on maintenance issues and ensure that the objective of maintenance cost reduction is achieved. This links logically with NCHRP Report 349 recommendations and the recommendations from other literature to have maintenance representatives provide input during the design stages of projects.

Whole Life Costing (WLC)

Constructing Excellence, an organization in the United Kingdom focused on improving the way the build environment is achieved and maintained, defines WLC as “the systematic consideration of all relevant costs and revenues associated with the acquisition and ownership of an asset” (CE, 2006). WLC is essentially a means of comparing options and their associated costs over a period of time. Costs that are taken into account include both initial capital or procurement costs, and future costs (CE, 2006) (Williamson & et. al., 2010). Woodward (1997) commented that the whole life cost of a physical asset begins when its acquisition is first considered, and ends when it is finally taken out of service for disposal or redeployment, when a new cost cycle begins (Woodward, 1997). The basic idea of whole life costing is similar to life-cycle cost analysis where a balance between initial and future expenditures is considered. WLC should not be considered in isolation as WLC is not an exact science. The technique is therefore often used in conjunction with other techniques such as risk management, VM, and VE (Langston, 2002).

Literature Review Summary

The findings from the literature review suggest that the inclusion of maintenance personnel in design will help reduce future maintenance costs and challenges associated with highway projects. However, the surveys undertaken by the previous research efforts suggest that maintenance personnel are not widely or consistently involved in project design. In cases where they are involved, the designers are not always able to address the issues raised by maintenance personnel. This current finding is clearly linked to the AASHTO strategic goal outlined in the introduction to this report: to support efforts to enhance the involvement of construction, maintenance, and operations personnel in the design phase of project delivery. The literature identified some techniques that can be used to reduce the maintenance costs of a project, such as incorporating life-cycle cost analysis and including maintenance activities in the preliminary design stages of a project. However, questions related to the likely return-on-time investment of these techniques on a project-by-project basis still remain.

REVIEW OF PRACTICE

This section discusses multiple options and “best practices” for incorporating maintenance considerations into highway and street design that have been developed and used by state and/or local agencies.

AASHTO Policy on Geometric Design of Highways and Streets (Green Book)

AASHTO’s Green Book provides current design research, policy, and practice for the geometric design of highways and streets. This document includes as its main audience highway engineers and designers who have the task of creating design solutions that meet the needs of highway users and other stakeholders while maintaining the integrity of the environment. This is also the key document to inform STAs when developing state-adopted design standards and policies that include design criteria.

The Green Book makes clear that maintenance operations and maintenance costs should be considered during the geometric design of highways and streets. The areas where maintenance considerations are recommended during design include:

- Right-of-Way (ROW) width;
- Side slopes;
- Drainage;
- Erosion control / landscaping;
- Medians on freeways / divided highways; and
- Considerations for different types of intersections and interchanges.

Washington State Department of Transportation (WSDOT)

WSDOT’s asset management program maintains and operates over 18,000 lane miles, approximately 2,000 miles of ramps and special-use lanes, and over 3,700 bridge and culvert structures, as well as hundreds of other special-use sites that constitute the state’s transportation system. Typical maintenance activities include patching potholes, cleaning ditches, painting stripes on the roadway, repairing damage to guardrails, and controlling noxious weeds. In addition to maintaining assets, operational services like plowing snow, cleaning rest areas, responding to incidents, operating structures like draw bridges, and operating traffic signals, lighting, and Intelligent Transportation Systems (ITS) are also provided. Best practices currently reported in WSDOT’s design manual are a culmination of responses from user surveys, interviews with maintenance and operations superintendents, and various regional practices that have shown promise in terms of potential improvements regarding the coordination of design and maintenance personnel.

Communication between people is the most fundamental component of the coordination. “Communicating early and often” with the “right people” will help achieve the best consensus and decision making between design and maintenance personnel. The following key points are made in the WSDOT design manual. It highlights potential areas and ideas that may increase the necessary communication between design and maintenance staff. These areas are summarized below.

1. *Maintenance Organizational Roles*: Depending on the scope of the project, the design team or the engineering division should consult with the appropriate maintenance discipline area (area maintenance, signal and ITS maintenance, traffic operational maintenance, and so on.) instead of the area maintenance office. This can be helpful in properly identifying issues and having them addressed at the design stage.

2. *Communicating Expectations*: A project’s design is usually heavily influenced by the subprogram and scope of a particular project. Maintenance staff do not generally work with these specific types of funding and project constraints. Hence, even if all issues raised by maintenance staff cannot be addressed on a particular project, these issues should be redirected to the region project management teams to evaluate their relevance to future projects.

3. *Communication Timing*: Maintenance staff have identified that project scoping through 30 percent design is the critical period for their input. This phase presents them with opportunities to evaluate and refine the options, as well as gain more understanding of the project constraints that may impact an identified or requested maintenance feature.

4. *Communication Methods*: Field reviews have been identified by maintenance staff as the primary and most effective method of communication. Multiple field reviews are recommended, in at least the following periods: 1) project scoping phase; 2) prior to the 30 percent design milestone; 3) each time a previously agreed-to maintenance feature is impacted through design iterations, as appropriate; and 4) prior to other major design review milestones.

WSDOT documentation also notes that a design project follows the basic principles of systems engineering. The design process generally consists of design iterations, which are necessary as information is gained through the process. Designers are constantly balancing stakeholder needs, regulatory requirements, design criteria, performance outcomes, and physical and political constraints. Throughout the course of the project, designers have to incorporate strategies related to project management and schedules and project reviews. Within a project management plan (PMP), representatives from different maintenance disciplines should be included, and their specific roles and responsibilities should be identified. This will ensure interdisciplinary decision-making and brainstorming of different options. During project scheduling, appropriate durations and timings should be scheduled to complete all necessary field reviews with maintenance staff. Appropriate durations should also be scheduled for procuring materials, to ensure that the project is being kept operational.

Maintenance stakeholders should be included in project review phases. They should be provided with visual aids and descriptions, in addition to sets of design plans, for better and easier assessment. Maintenance staff should never be in a position where they have to review project details from a plan sheet without a meeting/discussion, examples, or other means of communicating what features or issues should be the focus of their reviews. This effort will help ensure there are “no surprises” for maintenance and operations staff when the planned project enters construction.

Colorado Department of Transportation (CDOT)

CDOT’s Roadway Design Guide (2011) does not provide detailed information for incorporating maintenance considerations into highway design. It instead relies on the recommendations given by the AASHTO Green Book, expanding them to better fit CDOT’s needs. CDOT recommendations of areas where maintenance should be considered in highway design, and how it should be considered, are summarized in the following sections.

Vertical Alignment

CDOT notes that in all cases, the consideration of adequate sight distance requirements and other safety factors should take precedence over construction and maintenance costs.

Pavement – Surface Type

The selection of pavement type is determined by the volume and composition of traffic, soil characteristics, weather, performance of pavements in the area, availability of materials, energy conservation, the initial cost and the overall annual maintenance and service life cost.

The pavement structure should adequately support the expected traffic loads, keeping non-routine maintenance and traffic interruptions to a minimum.

Drainage Channels and Side Slopes

Modern highway drainage design should incorporate roadside safety principles, good appearance, control of pollutants, and economy of maintenance and construction. The above may be direct benefits of using flatter side slopes, broad drainage channels, and liberal warping and rounding. These features avoid obsolescence, improve appearance, and invite favorable public reaction.

Normally, backslopes should be 3:l or flatter to make it easier for motorized equipment to be used in maintenance. In developed areas, sufficient space may not be available to permit the use of desirable slopes. Backslopes steeper than 3:1 should be evaluated with regard to soil stability and traffic safety.

Clearance from Slope to Right-of-Way Line

The minimum clearance from the right-of-way line to the catch point of a cut or fill slope should be 10 feet for all types of cross sections, but the desirable clearance is 20 feet. Access for maintenance activities should be considered.

Slope Benches

For ease of maintenance, a 20-foot width of bench is satisfactory. Benches slope approximately 20:1 toward the roadway to prevent ponding of moisture behind the bench, thus creating additional slip plane problems. Benches should be constructed to blend with geologic strata rather than conforming to any set grade.

Traffic Barriers

Consideration should be given to the adaptability of the system to operational transitions, end treatments, and to the initial and future maintenance cost.

Tunnel Sections

Space should be provided for emergency walking and for access by maintenance personnel. Raised sidewalks, 2.5 feet wide, are desirable beyond the shoulder areas to serve the dual purpose of a safety walk and an obstacle to prevent the overhang of the vehicles from damaging the wall finish or the tunnel lighting fixtures.

Sidewalks

Sidewalk width may vary due to physical limitations, the presence of a separator between sidewalk and roadway, and the type of development the sidewalk serves. Four- to eight-foot wide sidewalks are normally used in residential areas and often a two-foot (minimum) planted strip is provided for maintenance. Where this strip is not present, an additional two feet of width is recommended.

Local Roads and Streets

If a sidewalk is placed away from a curb, a minimum of four feet should be provided. If the area is to be landscaped, a separation of eight to 10 feet may be needed for proper care and maintenance.

Right-of-Way (ROW)

When determining ROW widths, among other things, consider additional needs for maintenance and utility purposes. This additional width is desirable for maintenance access. For longitudinal barriers, among other things, consider maintenance concerns with snow drifting, ease of maintenance, and continuity of type and material.

Rural Freeways

Maintenance crossovers may be required at one or both ends of interchange facilities for the purpose of snow removal and at other locations to facilitate maintenance operations. The width of the crossover should be sufficient to provide safe turning movements and should have a surface capable of supporting the maintenance equipment used on it. Crossovers should not be placed in restricted-width medians unless the median width is sufficient to accommodate a vehicle length of 25 feet or more.

Urban Freeways

Median crossovers for emergency or maintenance purposes are generally not warranted on urban freeways due to the close spacing of interchange facilities and the extensive development of the abutting street network.

Interchanges and Grade Separations

Maintenance costs may differ by type of at-grade intersection configuration or interchange form. Interchanges have large pavement areas and variable roadside slope areas, the maintenance of which, together with that of the structure, signs, and landscaping, exceeds that of an at-grade intersection.

Pedestrian and Bicycle Facilities

Maintenance of pavement surfaces is critical to safe and comfortable bicycling. While regular maintenance activities will be required, some design treatments will help minimize maintenance needs:

- Place public utilities such as manhole covers and drainage grates outside of bikeways.
- Ensure that drainage grates, if located on or near a bikeway, have narrow openings and that the grate openings are placed perpendicular to the riding surface.
- Design of appropriate cross slopes should help to keep the riding surface clear of debris and water.

On unpaved shared use paths, grades greater than 3 percent can create maintenance (erosion) problems and create bicycle handling problems for some cyclists. One method of discouraging accidental motorist access to these shared use paths, particularly at intersections, is the use of a low, central, dividing island on the path approach to the intersections. Combined with tight curb radii, this method can be quite effective. The dividing island should be designed so that emergency and maintenance vehicles can access the path by straddling the island.

Some vegetative maintenance problems associated with bikeways can be mitigated during the design and construction of the facility. The following are examples of vegetation control methods that may be done before or during construction:

- Place a tightly woven geotextile or landscape fabric under the asphalt pavement. This method may be chosen in sensitive areas where a nonselective herbicide is undesirable. Several brands of geotextiles are available. Many provide additional structural support for the asphalt paving as well, and may allow reduced pavement thickness.
- Control undesirable “volunteer” vegetation and noxious weeds during construction.
- Use root barriers where they are beneficial to prevent root intrusion to the path surface. Suckering plants are the ones most likely to come through the path surface.
- Place a non-selective herbicide under asphalt paving. All applications must be done according to label directions. This herbicide will prevent vegetative growth from penetrating the asphalt paving for a number of years. Caution is needed in applying non-selective herbicides. They may injure nearby trees if their root systems grow into the treated area.

Snow and Ice Control

In designing roadways, roads should be designed to allow for snow storage. The roadside should have adequate space to place plowed snow so that it does not block a shared use path that may be adjacent to the roadway. Separation between road and path allows for snow storage at these locations.

Noise Regulations

For a noise mitigation measure to be feasible, it must be able to be constructible to normal engineering standards to provide a perceivable noise reduction. Walls cannot be more than 20 feet in height, and must not cause unsafe visibility or maintenance concerns such as obscuring egress visibility or creating a shadow zone resulting in persistent icing within a travel lane.

When considering construction of a noise barrier, maintenance factors should be addressed and any fatal flaws identified as early as possible to prevent problems later on in either design or operation. Examples of these factors include maintenance of the barrier itself, protective coatings, replacement of materials damaged by impact, cleaning of the barrier, graffiti prevention and removal, snow storage, and de-icing of the roadway in the winter months if shadowing is a problem. Plantings should be tolerant of the roadside environment and require little to no maintenance. It is particularly important to maintain a stock of replacement materials (i.e., posts, panels, blocks), which are compatible with the barrier in case damage does occur. Additional quantities should be considered in the construction package for contingency purposes. Usually access to the backside of the barrier is needed. Access can be provided with an access road, a walk path, gates, or access panels built into the barrier. Access must be designed so that it does not compromise the noise reduction effectiveness of the barrier. If the barrier is constructed on the right-of-way line, provisions should be made to coordinate the location of the access points with the appropriate agencies or landowners.

Wyoming Department of Transportation (WYDOT)

WYDOT's Road Design Manual (2015) mainly reiterates the maintenance considerations given in the AASHTO Green Book in the areas of ROW width, side slopes, drainage, and erosion control. Due to the snow conditions frequent in Wyoming during winter months, the design manual recommends that snow drifting be considered in cross-section design. Based on inputs from District Maintenance and a Blowing Snow Team, the cross-section design is carefully analyzed to ensure its adequacy under snow drifting situations. This consideration can ultimately have impacts on earthwork quantities in cases where the cross-section design is adjusted to mitigate snow drifting problems.

Maintenance history is one of WYDOT's considerations in design decisions for arterials, interstate highways, and state highways. This applies to the construction of new, as well as the 3R projects for these classes of roadways.

South Dakota Department of Transportation (SDDOT)

SDDOT's Road Design Manual provides criteria and coordination guidance for road design operations in compliance with the department's strategic plan, federal requirements, pertinent directives, studies, and technological advances. Maintenance operations and cost considerations are recommended in the same areas as those identified by the AASHTO Green Book. For SSDOT, the projects that involve bridge rehabilitation and repair require coordination between maintenance and design personnel, however this is not the case with new bridge constructions.

New York State Department of Transportation (NYSDOT)

Similarly, the NYSDOT identifies the same general maintenance considerations as those identified in the AASHTO Green Book. More detailed maintenance consideration is given to the design of medians and median crossovers. According to the NYSDOT Highway Design Manual, median crossovers are, among other items, needed to facilitate maintenance operations on controlled-access facilities. Maintenance crossovers may be required at one or both ends of an interchange. Crossovers may be provided on rural freeways when the interchange spacing exceeds 5 miles. The placement of the crossovers is coordinated with the Regional Highway Maintenance Engineer. Maintenance and emergency crossovers are not located within 1500 feet of the end of an interchange ramp. The minimum recommended crossover width is 25 feet. The median must be wide enough to store a typical maintenance vehicle. The surface and shoulders should be designed to support the appropriate maintenance equipment.

Additional maintenance considerations are also identified for highway drainage and roadside design. NYSDOT recommends input from maintenance personnel present when conducting drainage and roadside design.

California Department of Transportation (Caltrans)

Caltrans also identifies the basic maintenance consideration recommendations from the AASHTO Green Book. Additional design decisions that include maintenance considerations and require the input of maintenance personnel during design are in the areas of interchange type selection and Maintenance Vehicle Pullouts (MVPs). According to the Caltrans Highway Design Manual, MVPs provide parking for maintenance workers and other field personnel beyond the edge of shoulder. This is meant to improve safety for field personnel and free up the shoulder for its intended use. The need and location of MVPs is determined at project initiation. Caltrans notes that MVPs should only be provided if it has been determined that maintenance access from outside the state right of way through an access gate or a maintenance trail within the state right of way is not feasible. Where frequent activity of field personnel can be anticipated, such as at a signal control box or at an irrigation controller, the MVP should be placed upstream of the work site, so that maintenance vehicles can help shield field personnel on foot. If the controller or roadside feature is located within the clear recovery zone, relocating it outside the clear recovery zone should be considered. The shoulder adjacent to MVPs should be wide enough for a maintenance vehicle to use for acceleration before merging onto the traveled way. If adequate shoulder width is unattainable, sufficient sight distance from the MVP to upstream traffic should be provided to prevent maintenance vehicles from disrupting traffic flow. When considering drainage alongside an MVP, it is preferable to provide a flow line around the MVP rather than along the edge of shoulder to collect the drainage before the MVP. This will prevent ponding between the MVP and edge of shoulder.

Oregon Department of Transportation (ODOT)

In addition to the maintenance considerations specifically identified in the AASHTO Green Book, ODOT pays special attention to maintenance needs during roadside design. According to the ODOT Highway Design Manual, in the post-construction period, roadside maintenance is the most critical element in maintaining the designed function. The maintenance needs of new designs are considered as the project is being developed. Roads are designed and built according to established needs, and then appropriate maintenance is programmed to keep the facility safe and functioning. In the same way, the best practice in planning for roadside maintenance is a clear understanding of the functions to be maintained and then working to ensure ongoing maintenance capability. Participation of the maintenance personnel in project design and construction is critical for long-term success. Maintenance personnel are included when completing a roadside development initial project checklist. Maintenance personnel also participate in project development reviews, inspections, defining maintenance standards, developing maintenance agreements or contracts, creating maintenance plans for designed areas, defining the approximate maintenance resources needed, and analyzing and reporting on the ability of maintenance to meet new needs added by projects. In addition to the emphasis on roadside design, similar guidelines are provided and activities conducted for landscaping design and erosion control.

Arizona Department of Transportation (ADOT)

ADOT also identifies the same general areas as the Green Book where maintenance impacts of geometric design decisions should be considered. Their guidance recommends gathering input from maintenance personnel when designing medians and median crossovers along freeways and other divided highways. According to ADOT roadway design guidelines, maintenance and emergency vehicle crossovers between the divided roadways may be provided on controlled access highways. A list of median crossovers on Interstate highways has been prepared by ADOT’s Central Maintenance Group in coordination with its Traffic Engineering Group, the Department of Public Safety, and FHWA. In rural areas, maintenance and emergency vehicle crossovers may be provided between divided roadways as requested by the District Maintenance Engineer.

Nevada Department of Transportation (NDOT)

In addition to the same general recommended maintenance consideration identified by AASHTO, NDOT makes specific, focused efforts to include maintenance personnel in the design of emergency crossovers, railroad crossings, and special maintenance access points within the ROW, as documented in NDOT’s Road Design Guide. For maintenance and emergency purposes, when requested by NDOT Maintenance, the Nevada Highway Patrol, or other agencies, NDOT may, with adequate justification, provide emergency crossovers on rural freeways at an average spacing of not less than 2 miles where interchange spacing is 4 miles or greater. Special guidelines are also provided for railroad crossing design. All permanent structures over railroads require a minimum horizontal clearance of 12 feet on one side and a minimum of 18 feet on the other to provide for maintenance road access. The desirable clearance to provide for maintenance road access is 23 feet.

For controlled access facilities, maintenance access is provided between fence lines (or right of way) to the adjacent ROW fill slopes. The needed width of the maintenance access depends on the side slope and its type. Maintenance roads generally consist of a 4-inch aggregate base course. The need to provide paved maintenance roads should be evaluated on a case-by-case basis. Overhead signs and power lines are evaluated to ensure adequate clearance can be maintained for service equipment.

Minnesota Department of Transportation (MnDOT)

In addition to the maintenance considerations identified in the AASHTO Green Book, MnDOT has additional maintenance considerations for intersection design, particularly roundabout design, that refer to snow and ice operations, and routine or ordinary maintenance. MnDOT also conducts value engineering as part of their design process.

According to the MnDOT Road Design Manual, personnel involved in planning and design should identify design opportunities that may facilitate effective future operations for maintenance staff. Snow and ice operations are a particular concern and are the primary emphasis of maintenance considerations in Minnesota, while the secondary emphasis is on routine or ordinary maintenance. A goal of snow and ice operations is to effectively mitigate the visual impact that snow may have on the recognition of the roadway surface. It is important for snowplow operators to have landmarks available to successfully navigate roundabouts and their approaches. Without this guidance, unnecessary damage from the plow may occur to curbs, medians, light poles, and signage. Some considerations that may be easily incorporated into roundabout design that facilitate positive guidance to snowplow operators include:

1. Snowmelt should be considered when placing a drainage structure.
2. It is unlikely that 100 percent of the snow will be removed from the truck apron.
3. Multiple passes will be required to clear the intersection area of the roundabout. The focus of initial snow removal efforts is to clear the driving lanes. The roundabout design should accommodate snow storage space on the outer perimeter or away from the roundabout, which should be free from obstructions whenever possible. Snow storage space around the perimeter of the roundabout is limited.
4. The roundabout design should not have a ditch or swale behind the truck apron.

Routine maintenance required for roundabouts is similar to other intersection types. Two unique characteristics that deserve special considerations are landscaping and pavement markings.

1. A realistic maintenance program should be considered in the design of the landscape features of a roundabout. A local jurisdiction may pursue an agreement with MnDOT to provide maintenance to the landscaping details. However, when there is no interest from the local agency in maintaining the appurtenances, the design should consist of “hardscape” items and/or landscape plantings that require little or no maintenance. In all cases, the minimum sight distance triangles and blockage zones should be adhered

to. All roundabouts must provide some form of visual conspicuity in the central island to promote safety.

2. The landscaping plan should examine the possibility of creating a living snow fence into the design of modern roundabouts, especially in locations where drifting is likely. Locating trees, bushes, or shrubs to the northwest of the intersection may minimize drifting and facilitate effective snow removal.

3. Pavement markings provide positive guidance for vehicles as they approach a roundabout; they also require inspection and replacement on a regular basis. The striping equipment is large and has a wide turning radius. Maintaining striping within the roundabout may require significant handwork or it must be contracted to companies that have smaller and more mobile equipment. To minimize the maintenance efforts associated with pavement markings within the roundabout, a variety of design techniques can eliminate the need for pavement markings without eliminating the positive guidance needed to successfully navigate through the intersection. MnDOT suggests that different pavement types, colors, surfacing, and transitional curbing can provide visual feedback to drivers and facilitate movement through the roundabout in lieu of pavement markings.

Value engineering studies that MnDOT includes in their design process provide a significant benefit since the actual dollars spent on highway design are comparatively small when compared to the contribution of construction and maintenance operations in terms of total life-cycle costs. However, decisions made in planning and design have greater impacts on total life-cycle costs than those decisions made in construction and maintenance. Therefore, a relatively small investment in time and money during design can lead to substantial savings over the project life.

Indiana Department of Transportation (INDOT)

INDOT also identifies the general AASHTO guidelines for maintenance considerations relevant to the geometric design of highways and streets. However, INDOT also provides maintenance-related guidance for ROW design and explicitly includes value engineering principles that combine various considerations when executing a design project. According to the INDOT Road Design Manual, the overall ROW width should be increased to provide additional width for maintenance, in the form of a six- to 15-foot area that is provided along each side of the roadway to accommodate maintenance equipment at the top or bottom of a cut or fill slope.

INDOT’s value engineering process uses a team approach to review all aspects of a project: design, procurement, construction, operation, and maintenance. Each VE team is made up of five to seven individuals with a variety of expertise to study the major problem areas anticipated for the project, such as traffic, right of way, structures, soils, materials, construction, design, and maintenance. Due to cost and time constraints, the team will normally only review 20 percent of the project elements which account for approximately 80 percent of a project's total cost. For the greatest benefit, INDOT notes that value engineering should be implemented as early as practical in the project development process.

Florida Department of Transportation (FDOT)

In its Plans Preparation Manual, FDOT provides insights to maintenance considerations of design decisions that are primarily focused on roadside slopes. According to the manual, for slopes steeper than 1:3, the associated long-term erosion control and maintenance costs should be considered. Coordination for the use of these slopes should be made with the drainage, maintenance, and landscape groups. For sod or turf slopes steeper than 1:3 and higher than 20 feet, a 10-foot-wide flat area at the top and base of the slope should be included, with clear access for maintenance equipment and personnel. For sod or turf slopes steeper than 1:3 and higher than 35 feet, a 10-foot-wide maintenance berm should be included, not more than every 35 feet from the top of the slope. Other maintenance considerations correspond to those identified in the AASHTO Green Book.

Summary of Practice

From the review of practice, it can be seen that most STAs consider it important to incorporate maintenance costs and considerations into highway and street design, but there is not much explicit or detailed guidance on how to do so. The considerations identified by various STAs include those associated with ROW width, side slopes, drainage, erosion control/landscaping, medians on freeways and other divided highways, and intersection/interchange type selection.

AGENCY SURVEYS

In order to further explore the current state of practice and future needs related to incorporating maintenance costs and considerations into highway designs during various stages of project development, the research team distributed a web-based survey to design and maintenance staff within multiple STAs. The survey consisted of twenty-seven questions covering different aspects of maintenance considerations and maintenance personnel involvement in design decisions. The complete survey questionnaire is provided in Appendix 1 of this Report. The survey was distributed to UDOT Region Preconstruction Engineers, District Engineers, Area Supervisors, and some Project Managers, Design Squad Leaders, and Central Maintenance staff. The survey was also sent to AASHTO Subcommittee on Design and Subcommittee on Maintenance contacts from other federal Region 8 states: Colorado, Montana, North Dakota, South Dakota, and Wyoming. Thirty-one surveys were returned, with different response rates to different questions. The survey respondents included personnel from Utah DOT, South Dakota DOT, and North Dakota DOT. While not all survey respondents provided contact information, a majority of survey responses appeared to come from UDOT. A question-by-question summary of responses to the survey is provided in Appendix 2, with a slightly more detailed, quantitative and graphical analysis in Appendix 3.

Survey Results Overview

Approximately 77 percent of survey respondents indicated that their agencies have a process of evaluating the maintainability of highway and street designs that includes identifying likely maintenance problems and communicating needed changes to the designers. The opinions of the respondents on whether the process for evaluating the maintainability of highway and street designs is formal or informal was equally divided. Some responded that their process is both formal and informal, depending on the phase/status of the design. During some design stages, respondents noted that there are formal internal meetings on maintainability reviews, while for the other stages, the maintenance input is considered informal.

About half of the respondents who replied to the question on available documentation for evaluating the maintainability of highway and street designs (including documentation on an agency's website) were able to identify such a document. Usually, identified documents described maintenance and preconstruction site visits, or were the STA's roadway/highway design or project development manuals. All the respondents who replied to the survey agreed that maintenance personnel are currently involved in the process for evaluating the maintainability of highway and street designs at their agency in some way. There was also a high level of agreement among the survey respondents that maintenance personnel are involved in most project-related meetings (kick-off, scoping, design, Plan, Specification and Estimate (PS&E), preconstruction, construction, post-construction) and site visits throughout the design and construction process. They are usually asked to provide input on current maintenance issues as well as on the proposed design with the goal of delivering a more maintenance-friendly design. Their input is usually based on the design needs and previous experiences with similar projects.

Based on survey respondent replies, they see communication, unfamiliarity with the design process, and attendance at all project meetings as some of the major problems and challenges associated with involving maintenance personnel in the design process. Approximately 65 percent of the survey respondents who replied agreed that they experienced significant maintenance problems at some time that resulted from insufficient consideration of maintenance during the design process. These problems were usually project and site specific, but some of the more common ones based on the survey replies included maintenance issues associated with snow storage, side-slope design, drainage, signage, and guardrails.

Approximately 65 percent of the respondents who replied said there were maintenance challenges associated with innovative intersection/interchange designs (such as CFIs, DDIs, or Median U-Turns). Most of them agreed that the main maintenance challenge with these designs was snow removal. When asked to rank the importance of different factors in evaluating alternative highway and street designs, three factors clearly came to the very top of the list: 1) traffic operational efficiency and quality of service, 2) traffic safety performance, and 3) compliance with established design criteria, all of which were ranked as high priority in more than 80 percent of the survey responses. Maintenance costs and considerations were assigned mainly a low importance level in most respondent replies.

Respondents agreed that, in most cases, the design team and project manager make the evaluations of alternative highway and street designs. Close to 75 percent of the respondents who replied agreed that designers and maintenance personnel used the special maintenance needs of past designs to change future designs and design practices. It was not quite clear from the replies when these assessments and discussions take place, but a majority of respondents indicated that this is happening early in the design process when there is still opportunity for significant adjustments. The process used to implement the results of these discussions was also vague among the survey respondents, so no clear conclusion can be drawn from the survey responses on design changes that have been made as a result of maintainability reviews. The most common noted result of the maintenance reviews was a change in the design plans, but a majority of the survey respondents who replied could not give an actual project example of where the discussions led to an actual change in design drawings and practice. Some identified possibilities where respondents believed that changes were made based on maintenance input included rumble-strips standard designs drawings, culvert end sections, and a modification of median curbs to improve snow-plow operations. Some other common design solutions that were primarily developed to alleviate future maintenance problems and reduce maintenance costs included guardrail cable barrier and concrete barrier design, side-slope design, grooved-in pavement markings, and replaceable delineators.

Value engineering, which is a systematic review of projects and processes to improve their performance, quality, and life-cycle cost by a multidisciplinary team, was considered important among all the respondents who replied to this question, and 90 percent of them indicated that this process is being used by their agency. A bit more than half of respondents were able to provide the document/link that explained the value engineering process within their agency and its requirements. The inclusion of maintenance personnel in the value engineering process was noted as a common practice by only about 30 percent of survey respondents, meaning that this still may not be a common practice.

Almost all respondents, 95 percent, said their agency is using innovative contracting methods in design. However, the role of maintenance personnel and their level of involvement with these methods were unknown in most cases. Approximately 63 percent of survey respondents indicated that innovative contracting methods led to maintenance challenges. These challenges were mostly project specific, but it was recognized that insufficient consideration of maintenance and lack of communication led to the maintenance challenges and also may have led to non-compliance with design standards and criteria.

FRAMEWORK FOR PHASE II WITH RESEARCH RECOMMENDATIONS

This section includes a framework for incorporating maintenance costs and other maintenance considerations into highway design decisions during different project development stages. The framework is intended to be comprehensive as it identifies relevant maintenance-related inputs for making cost-effective design decisions. Input from the project TAC on this framework, as well as on other key findings from the literature review and survey summarized in previous sections of this report, were used to identify priorities for expanding the framework elements based on criteria such as total maintenance budget, potential for cost cutting, data availability, and other criteria offered by the TAC. Each subsection of this framework therefore concludes with a recommendation of whether or not that portion of the framework was further studied and expanded during the second phase of the project. Additional research related to the following four sections of the framework were recommended for the second phase of the project:

- Barrier type selection
- Drainage
- Cross-section elements and temporary traffic control
- Intersection and interchange form and design

The following three sections of the framework will not be expanded during the remainder of this project:

- Roadside slopes and right-of-way
- Pavement, bridges, traffic control, and advanced traffic management
- Design and maintenance communication

Roadside Slopes and Right-of-Way

Key questions related to roadside slopes and right-of-way in the literature and survey responses seemed to center around roadside slopes and right-of-way costs versus ease of maintenance-related access and operations. NCHRP Report 349 noted that flat roadside slopes with rounding minimized erosion potential and made maintenance operations easier. NCHRP Report 349 also suggested considering the purchase of more ROW to allow for roadside designs that can be more easily maintained, as well as placing ROW elements, including fencing, noise walls, and gates in locations that do not cause future maintenance access and ownership issues. Designing minimal-maintenance landscaping and providing adequate access to roadside features requiring maintenance were also identified as important issues. General roadside design guidance was provided in the literature and, in many causes, was consistent with roadside safety principles. For more in-depth analysis, data on the construction, ROW, maintenance, and safety costs of various roadside design alternatives would need to be collected and analyzed.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will not be expanded during the second phase of this project due to the lack of enough objective data associated with how the roadside environment impacts maintenance activities (e.g., time, difficulty, staff needs).

Barrier Type Selection

Barrier type selection typically considers performance capability, deflections (versus available area for deflection), site conditions, compatibility with terminals or transitions to other systems, cost, maintenance, aesthetics, and field experience. Maintenance-related considerations identified in the literature and existing design policies included:

- Routine maintenance, with few systems generally needing significant amounts of routine maintenance;
- Collision repairs, with flexible or semi-rigid systems requiring significantly more maintenance after a collision than rigid or high-performance systems;
- Material storage, noting that the fewer the number of different systems a state utilizes, the fewer inventory items/storage space required; and
- Simplicity, with simpler designs being easier to maintain and more likely to be reconstructed properly by field personnel.

One survey respondent suggested using the expected number of roadside encroachments as an input to barrier type selection, with an idea of using barrier types with less maintenance and repair needs where roadside encroachments are expected to be more frequent.

Other survey respondents identified litter build-up/removal and ice resulting from a “shadowing effect” as key inputs to barrier type selection. The shadowing effect and potential for snow accumulation was also identified in the broader research literature, but the “shadowing effect” was primarily related to noise walls. A more in-depth analysis of the maintenance and repair costs associated with barrier type selection, combined with the other considerations noted above, is another possibility for a promising study if data are available.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will be expanded during the second phase of this project with additional data collection and analysis. Specifically, the research team will attempt to characterize: 1) the range of roadside barrier types and impact attenuators involved in crashes throughout Utah, 2) the extent of damage to these hardware systems as a result of crashes, 3) the level of injuries sustained by drivers and occupants involved in crashes with different barrier types and impact attenuators, and 4) the collision repair process and costs for different systems. If successful, the results of these analyses are expected to provide insights into how collision repairs, material storage, and design simplicity can be quantified and considered when making future decisions regarding barrier type and impact attenuator selections, while also fully considering potential safety effects.

Drainage

Identified maintenance issues related to drainage design involved accessibility for cleaning and other maintenance, erosion control, resistance to corrosion, debris accumulation, and having enough ROW for repair operations. Some general recommendations for drainage design to minimize maintenance challenges were offered in the literature. Drainage design decisions were identified by two survey respondents as the decisions that often cause the most significant maintenance challenges. Initial steps toward a more-depth investigation of drainage-related challenges could start with a set of “effective” and “challenging” drainage design examples with pictures and descriptions, followed by estimates of additional maintenance costs and construction cost savings associated with the more challenging drainage designs.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will be expanded during the second phase of this project with additional information gathering. The additional information gathering will be qualitative with an ultimate goal of producing a series of case studies showing drainage designs that are effective and challenging from a maintenance perspective. The case studies can possibly provide tangible examples for designers that build on general guidance to consider accessibility for cleaning and other maintenance, erosion control, resistance to corrosion, debris accumulation, and having enough ROW for repair operations. Potential case studies will be identified by reaching out to UDOT Region Preconstruction Engineers, District Engineers, Area Supervisors, and some Project Managers, Design Squad Leaders, and Central Maintenance staff who received the Phase I survey, particularly those who identified drainage design as a high-priority issue for this project.

Cross-Section Elements and Temporary Traffic Control

This category of the framework is intended to capture the selection of physical highway and street dimensions, particularly cross-section dimensions, to support future maintenance activities and associated temporary traffic control. Some specific examples provided in the literature and in the survey responses included: 1) temporary traffic control setup and user costs associated with pavement repairs and rehabilitation for various pavement design and cross-section design combinations, 2) whether or not traffic lanes needed to be closed to repair guardrail, 3) and providing adequate shoulder widths, particularly median shoulders, for maintenance operations. While it would be expected that a majority of cross-section designs could accommodate future temporary traffic control on state roads, it may be worth further exploring how small changes in cross-section dimensions or criteria could improve future maintenance operations and reduce corresponding user costs. Median shoulders next to median barriers was the case specifically identified by one survey respondent.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will be expanded during the second phase of this project with additional information gathering, data collection, and analysis. Specifically, the research team will use a combination of literature synthesis, surveys, and analytical studies to revisit design criteria and design decisions related to median shoulder width on divided highways, with a focus on segments with median barriers. It was recognized during the TAC meeting, however, that median shoulder width could not be looked at in isolation. The study, therefore, will look at design criteria and decisions related to the entire directional roadway cross section (i.e., lane number/lane width/shoulder width combinations) on divided highways with median barriers and determine overall impacts of cross-section design alternatives on safety and operations, including maintenance costs that capture types and frequencies of maintenance needs (e.g., catch basins, signs, sweeping), temporary traffic control (TTC) needs during maintenance, safety, and other user costs. The TAC noted that the results of this study may be particularly useful when design exceptions for median shoulder width criteria are being considered and analyzed.

Intersection and Interchange Form and Design

State agency documentation noted that maintenance costs are likely to differ by type of at-grade intersection configuration or interchange form. Interchanges have large pavement areas and variable roadside slope areas, the maintenance of which, together with that of the structure, signs, and landscaping, exceeds that of an at-grade intersection.

Snow plowing, snow storage, pavement markings, signs, and temporary traffic control were specifically identified in the literature and reinforced by survey respondents as key maintenance considerations. Eight survey respondents noted challenges with snow plowing arising from various intersection design alternatives related to snow removal and storage, with particular emphasis on storing the snow, particularly when there are bike lanes that must be clear. At least one survey respondent noted the inability to see islands when snow is deeper.

Other points made in both the literature and survey responses were related to the need to inspect and replace pavement markings and signs on a regular basis, with some intersection forms requiring more markings than others. It was also noted that striping equipment is usually large with a wide turning radius. Maintaining striping within the intersections with “tighter turning” may require significant handwork or it must be contracted to companies that have smaller and more mobile equipment.

Building on this focus area of the framework could involve collecting data and information on maintenance-related costs associated with various aspects of intersection and interchange designs and determine if they are at a comparable magnitude to safety and operational benefits/impacts of the designs.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will be expanded during the second phase of this project with additional information gathering. The additional information gathering will be qualitative with an ultimate goal of synthesizing practices in other states for signing, markings, and snow operations at new/innovative at-grade intersection designs. As part of the synthesis, the research team will seek to identify any specific changes to these practices that have been made as a result of maintenance experiences.

Pavement, Bridges, Traffic Control, and Advanced Traffic Management

One survey respondent identified maintenance issues associated with shoulder treatments, another with soft spot identification, and a third wrote only "bridge approaches" for areas causing significant maintenance challenges, but no additional details were provided. That said, bridges and pavements are the "big ticket" cost items where significant cost savings could be realized if potential changes in design to support efficient maintenance are identified. TAC input is needed on the availability of maintenance data for bridges and pavements that would be worth exploring and that could uncover potential maintenance-related cost savings. There was also no significant focus uncovered in the literature on specific maintenance considerations for selecting traffic control and advanced traffic management infrastructure.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will not be expanded during the second phase of this project due to the fact that any one of these "big ticket" items could consume the entire project. The original vision for this project was to focus on a range of other types of decisions (e.g., geometric design) that were of interest to the TAC for analyzing from a maintenance perspective.

Addressing Challenges with Design and Maintenance Communication

Both the literature and survey responses indicated challenges associated with getting maintenance personnel effectively involved in the process of evaluating the maintainability of highway and street designs. These challenges included time and resources for maintenance staff to attend meetings and provide input, technical expertise of both designers and maintenance personnel in each other's areas, getting maintenance to feel involved in design instead of the design being forced on them, and open communication on why various suggestions could not be implemented so as not to discourage future participation.

Training and outreach to Design on design-related maintenance problems and to Maintenance on desired types, timing, and value of maintenance input is one possible solution. NCHRP Report 349 noted that the design training and outreach on design-related maintenance problems could include suitable visual aids and site visits and videos to observe a variety of maintenance challenges in the field. Training for Maintenance could include background on plan reading in order to more fully understand how designs could impact maintenance operations. An effective part of the training and outreach to the design and maintenance groups, as well as to high-level management, could include case studies and a measurement system to evaluate the effectiveness of the process of maintainability reviews when effectively implemented. This could encourage continuation of the process and more active participation. NCHRP Report 349 suggested in-depth reviews of several projects to identify "success stories" or needed improvements. This review process could be implemented periodically to determine if improvements are being made in terms of the amount and effectiveness of maintenance participation.

Executing this portion of the framework would involve working with both design and maintenance staff to develop training material and case studies as described above.

Based on recommendations from the project TAC and follow-up assessments by the research team, this portion of the framework will not be expanded during the second phase of this project due to already on-going initiatives within UDOT to increase communications and interactions between design and maintenance groups.

PHASE II

QUANTIFICATION AND ANALYSIS OF LONG-TERM COSTS OF BARRIER SYSTEMS

As described above in Phase I, the TAC identified a total of four potential topics where long-term maintenance costs could be prioritized for further analysis. Based on the potential availability of data and on input received by the research team, the first priority topic was related to analysis of barrier systems, followed by a secondary objective to analyze drainage-related assets.

For barrier systems, the following major cost groups were identified for further evaluation and in anticipation of the goal of providing inputs for future life-cycle cost analyses:

- Installation / construction costs
- Maintenance costs
- Other project costs / crash-related costs

In terms of barrier types, general barrier system groups of interest were also identified based on comments from the TAC, description codes on preliminary data from UDOT financial systems, and also reviewing the asset inventory datasets available online from UDOT's data portal. Barrier types were ultimately categorized, at a minimum, into four categories, including:

- Concrete barriers
- Guardrails
- Cable barriers
- Attenuators

As expected, a large number of sub-categories were also considered within each group, and these are included in the different cost category analysis below. These subcategories also include special or custom items, often identified by special characters and trailing character codes in the agency's item coding system. For example, a W-beam guardrail is typically identified by item codes 0284100XY where X specifies the post material (e.g., 8 for wood and 9 for steel), and Y specifies the post length (e.g., 72 inches or 84 inches). However, some item codes identify special items, particularly by varying the last character in the code, including an asterisk (*). Such items may be more susceptible to different initial or project-related costs and could also be analyzed separately.

The team then proceeded to coordinate access to UDOT's work order and expense records, with the goal of extracting and classifying costs related to barrier type and cost categories listed above. This process involved direct access to querying tools by the team, as well as meetings to coordinate data extraction with UDOT’s employees with further access to internal databases.

The next subsections describe the extraction process and present summary costs to characterize each cost category. Then, costs are adjusted for inflation using a multiplicative factor derived from historic consumer price indices (CPI), so the adjusted costs can be used in present analyses. It is noted that extensive efforts were focused on data post-processing needs, where both automated and manual processes were applied to the data for proper re-classification.

Installation costs are described next, followed by maintenance costs, other project costs, final adjusted costs, and an illustration of an applicable life-cycle cost framework.

INSTALLATION COSTS

Installation costs are based on costs extracted from the Project Development Business System (PDBS). PDBS is a highway construction management tool and database that allows UDOT, consultants, and contractors, to document and control construction projects.

Instead of having direct access to PDBS, the research team met Aaron Watson, a Construction Project Close-Out Specialist Consultant at UDOT, who explained how PDBS stores construction costs and how information could be queried using the system. This discussion resulted in the research team providing Mr. Watson with a list of key item names, so cost estimates related to those items could be queried for projects awarded within the 10-year span covered by the analysis period (between September 2008 and August 2018). The list of key item names used in the queries are shown below in Table 1.

Table 1. Item Names for PDBS Queries Related to Barrier Systems

Barrier Systems - Item Description Names	
Guardrail	Half Barrier
Crash Cushion	End Treatment
Cable Barrier	Bridge Parapet Departure Bracket
Concrete Barrier	Cable Attachment Rail
Concrete Constant Slope Barrier	Tension Gauge
W Beam, WBeam	Cable Posts

After extraction, individual files for each of the queried items were received and compiled into a new database. Each record in the database described the item in the project bid, an item code associated with the described item, the estimated and adjusted quantities of the item, the estimated unit cost, and the actual amount paid for the item. As mentioned above, item codes were associated with standard items in UDOT's Standard Specifications, which allowed for identification and grouping of similar items to develop more general categories.

Raw PDBS data presented several challenges and required significant post-processing for successful analysis. For example, several revisions were made to UDOT's Standard Specifications during the study time period (2008-2018), resulting in significant differences in item numbers, descriptions, and classifications over time. Practically, this meant that extracting information about a certain item (e.g., a type of guardrail) could result in needing to track multiple item codes, or search for a number of different keywords in the item descriptions to find matching items in the database. Additionally, since item codes often have modifying codes (e.g., asterisk, or "P"), and these modifying codes take the place of the last character in the item code, it may become difficult to find matching items in the database.

Searching by item description was not straightforward given that the item descriptions often exceed the character limit for PDBS's export tool, resulting in many records with cut-off or abbreviated text. Continuing the example of the W-beam guardrail from the previous section, Table 2 shows different description examples for W-Beam Guardrail 72-inch Wood Posts where the item codes are the same (identified with an ending character "P" in this case) but have different item descriptions. However, it is evident that the initial 8 characters classify the same item group. It is noted that unit costs for items with modification codes are not necessarily higher than standard ones.

Table 2. Example Modifying Code Descriptions for W-Beam Item in PDBS

Item Number	Description	Unit Price
028410086	W-Beam Guardrail 72 inch Wood Post	22.66
02841008P	W-Beam Guardrail 72 inch Wood Post - Aci	17.9
02841008P	W-Beam Guardrail 72 inch Wood Post - Sti	24
02841008P	W-Beam Guardrail Connect to Existing Pos	20

In order to address the issues summarized above, database items were reclassified based on combinations of item codes and item descriptions. This process involved checking item codes and item descriptions against standard specification documents, finding common descriptions where possible, and adding multiple classifying tags to each database entry.

For example, an item identified as a "W-Beam Guardrail Median Barrier" would be classified as being a W-beam guardrail barrier, with an attached attribute indicating its use at the median. Additional attributes were added for sizes (e.g., guardrail post length), materials (e.g., pre-cast concrete), and other attributes (e.g., barrier post spacing), simplifying database queries and proving a means for summarization across broader descriptions than those originally found in the PDBS database.

Requesting cost estimates for a W-beam guardrail from the original PDBS data would have required either choosing a specific item from the long list of W-beam guardrail items available, or picking a representative item to reflect the estimated cost. The modifications made to the database now accumulate multiple W-beam guardrail items into a class described as a Guardrail for summary statistics describing item costs, and the user may further modify the query to extract more specific items.

Installation Cost Tables

The database provides three different types of cost estimates – paid unit costs based on original quantities, paid unit costs based on adjusted quantities, and estimated unit costs from PDBS. From discussions with the TAC, adjusted quantity likely reflects the actual quantity of the item which was ultimately installed/constructed. Out of an abundance of caution, a separate estimate for paid unit costs is provided based on both quantities. The paid unit cost is calculated as the actual paid amount divided by the quantity. The estimated unit cost comes directly from the PDBS database (i.e., the unit cost estimated from PDBS data for the bid item).

Costs are summarized by the average cost, weighted average cost, median cost, and the interquartile range for costs. The average cost is calculated as the simple average of the unit costs over bid item records. That is, the average cost is calculated as the average taken over each observed record in the database matching the query (e.g., cable barrier), regardless of the quantity purchased for that item. The weighted average cost accounts for both the costs and quantities, giving more weight to costs where higher quantities were purchased. The weighted average cost better describes the average unit cost of all items constructed in a given item description/class, where potentially lower prices associated with large quantities may be a factor.

The simple average cost better describes the typical cost for smaller projects, where prices may not be affected when purchased in smaller quantities. The median represents the calculated 50th percentile estimate based on matching queries in the database, and the interquartile range represents the 25th and 75th percentiles in the same query. The median and interquartile ranges are calculated based on record observations and do not consider quantities purchased in each record. These percentile measures offer more information about the distribution of the cost records associated with an item query. The 25th and 75th percentile ranges are provided primarily to avoid issues with extreme values in the distributions. This is important to keep in mind when examining costs based on records with item code modifiers, where the modifier may indicate a significant deviation from the item standard specification, and hence result in a cost estimate farther from the mean or median.

Summaries for the three cost estimates are provided in Tables 3 through 5 for all items together (with and without modifiers). Each table indicates both the original estimated quantities and the adjusted quantities associated with an item query. Additionally, the tables indicate the number of records matching the item query. These details help to indicate the number of observations used to provide cost estimates in the table. Two different values are provided to describe the number of records – the total number of records matching the query, and the number of records in which costs are available within the query. This is an important detail because the summary table was produced under the assumption to ignore records with negative or zero costs, and differences between these record counts can be attributed to this factor.

Table 3. Paid Initial Unit Costs Based on Original Quantities for Standard Barrier Types – All Items

Paid Unit Cost, All Items												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	84	10%	$11.57	$23.60	$17.54	($13.03 - $25.23)
Attenuator	Any	Any	Each	4,345	4,218	742	665	4%	$4,493.12	$6,542.82	$3,325.00	($2,600.00 - $7,588.34)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	16	13%	$23,714.44	$27,992.44	$24,935.00	($20,125.00 - $34,750.00)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	65	7%	$18,808.66	$19,129.20	$16,800.00	($14,000.00 - $24,200.73)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	40	7%	$4,883.11	$5,191.98	$4,500.00	($4,063.75 - $5,310.25)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	14	11	8	7	2%	$25,955.50	$25,590.71	$26,000.00	($24,500.00 - $26,460.00)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	90	4%	$8,939.41	$9,389.60	$8,320.00	($7,638.00 - $9,615.75)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	304	3%	$3,084.85	$3,336.68	$2,900.00	($2,550.00 - $3,459.99)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	29	5%	$3,582.32	$3,358.45	$3,100.00	($2,900.00 - $3,531.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	110	4%	$2,487.60	$2,756.63	$2,358.13	($2,100.00 - $2,897.50)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	13%	$4,111.76	$3,516.67	$3,400.00	($3,100.00 - $3,875.00)
Concrete	Any	Any	Feet	378,330	373,284	188	161	4%	$43.71	$68.67	$57.13	($47.77 - $80.00)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	20	9%	$67.34	$80.79	$77.32	($65.18 - $84.44)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	130	5%	$43.45	$66.51	$55.00	($46.56 - $74.01)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	12	14%	$83.17	$89.75	$82.77	($65.18 - $106.44)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	6%	$81.86	$74.73	$78.03	($65.18 - $83.14)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	145	5%	$44.88	$67.64	$56.00	($47.77 - $74.64)
Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	12	14%	$62.25	$84.84	$77.32	($67.12 - $86.99)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	129	5%	$43.44	$65.91	$55.00	($46.55 - $73.47)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	668	3%	$22.15	$31.78	$25.00	($18.61 - $37.09)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	310	6%	$21.74	$27.85	$21.96	($17.84 - $31.68)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	147	6%	$21.72	$29.55	$22.00	($18.01 - $32.36)

Table 4. Estimated Unit Costs (from PDBS) for Standard Barrier Types – All Items

Estimated Unit Cost (PDBS), All Items												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	95	7%	$11.77	$19.63	$16.10	($13.00 - $22.00)
Attenuator	Any	Any	Each	4,345	4,218	742	740	4%	$4,107.95	$5,734.53	$3,185.00	($2,600.00 - $7,408.89)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	19	7%	$20,000.00	$21,889.55	$21,800.00	($20,250.00 - $24,935.00)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	70	2%	$15,508.32	$16,116.61	$15,780.00	($14,210.00 - $17,500.00)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	46	3%	$4,356.51	$4,468.15	$4,385.00	($4,162.50 - $4,637.50)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	14	11	8	8	3%	$27,111.07	$26,141.88	$26,000.00	($24,850.00 - $27,065.00)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	101	2%	$7,770.29	$8,156.84	$8,000.00	($7,600.00 - $8,715.53)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	318	1%	$2,812.50	$2,940.22	$2,850.00	($2,552.50 - $3,200.00)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	54	5%	$3,714.52	$3,808.45	$3,350.00	($3,054.25 - $3,992.50)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	117	8%	$2,240.01	$2,553.13	$2,300.00	($2,060.00 - $2,537.09)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	5	11%	$4,284.90	$3,663.49	$3,400.00	($2,947.47 - $4,350.00)
Concrete	Any	Any	Feet	378,330	373,284	188	188	3%	$43.31	$61.87	$55.00	($48.00 - $69.52)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	21	7%	$66.98	$78.23	$75.00	($59.50 - $85.00)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	155	3%	$43.04	$58.24	$52.70	($46.00 - $63.00)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	13	11%	$87.64	$107.98	$85.00	($80.00 - $153.37)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	12%	$82.19	$86.53	$82.63	($68.57 - $87.25)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	171	3%	$44.38	$58.82	$53.24	($47.89 - $63.69)
Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	13	7%	$61.74	$73.13	$68.00	($56.50 - $80.00)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	154	3%	$43.03	$57.69	$52.70	($46.00 - $63.00)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	749	2%	$22.48	$27.95	$24.16	($19.05 - $32.25)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	329	2%	$20.93	$24.23	$21.00	($18.00 - $28.50)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	161	3%	$19.70	$23.38	$21.00	($18.00 - $26.30)

Table 5. Paid Initial Unit Costs Based on Adjusted Quantities for Standard Barrier Types – All Items

Paid Unit Cost, Adjusted Quantities, All Items												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	83	10%	$11.57	$23.69	$17.22	($13.36 - $25.25)
Attenuator	Any	Any	Each	4,345	4,218	742	663	4%	$4,471.52	$6,388.07	$3,336.67	($2,600.00 - $7,500.00)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	16	13%	$22,896.70	$27,055.44	$23,967.00	($17,442.50 - $34,750.00)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	64	6%	$19,561.00	$18,806.83	$16,736.03	($14,000.00 - $24,400.55)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	39	6%	$5,360.19	$5,284.05	$4,500.00	($4,117.50 - $5,373.50)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	14	11	8	7	2%	$25,955.50	$25,590.71	$26,000.00	($24,500.00 - $26,460.00)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	90	4%	$8,835.46	$9,125.17	$8,320.00	($7,638.00 - $9,615.75)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	304	3%	$3,081.82	$3,244.98	$2,900.00	($2,550.00 - $3,459.99)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	29	5%	$2,949.48	$3,211.59	$3,040.00	($2,900.00 - $3,450.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	110	4%	$2,494.14	$2,725.77	$2,358.13	($2,100.00 - $2,897.50)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	13%	$4,111.76	$3,516.67	$3,400.00	($3,100.00 - $3,875.00)
Concrete	Any	Any	Feet	378,330	373,284	188	161	4%	$43.83	$68.01	$57.13	($47.77 - $78.75)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	20	9%	$67.10	$80.74	$73.97	($65.18 - $83.14)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	130	5%	$43.62	$65.70	$54.83	($46.56 - $73.19)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	12	14%	$83.17	$89.75	$82.77	($65.18 - $106.44)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	6%	$81.86	$74.73	$78.03	($65.18 - $83.14)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	145	5%	$45.03	$66.91	$56.00	($47.77 - $74.40)
Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	12	14%	$61.95	$84.75	$73.63	($67.12 - $81.76)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	129	5%	$43.61	$65.09	$54.66	($46.55 - $72.35)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	666	3%	$21.37	$30.58	$24.91	($18.37 - $36.00)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	310	3%	$20.27	$25.46	$21.18	($17.66 - $30.55)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	146	6%	$22.34	$29.25	$22.18	($18.19 - $32.41)

Additional tables were also generated separately for items with no item modifiers and for those with a modifier, and also for the three cost estimation methods, resulting in the six tables included in Appendix 3. As mentioned above, asterisks indicate a “Special Provision” is present in the bid documentation for specific items, and they may indicate a significant deviation from the standard description for the item code, which could result in different cost estimates for those items.

MAINTENANCE COSTS

Maintenance costs were perhaps the category with the most unknowns in the process, and the one that required the most pre-processing. During the initial data analysis, it was apparent that direct and unambiguous associations between maintenance costs and specific barrier elements at a given location could be established. This was evidenced by details in the work order records, the different system reports, and the actual tracking of specific costs categories, including labor, equipment, and material costs, as described below.

For this analysis, the research team was directed to access and extract expense records from online services provided by UDOT which are contained in two different systems:

1. OMS (Operations Management System), and
2. FINET (Utah's Financial Network System)

Data access was allowed through a website at https://oms.udot.utah.gov/, where specific tables were created for this project and labeled "UofU table" in the report templates. Reports accessible through this interface provided the team with work orders from OMS, work order costs from FINET, and FINET transactions.

Generally, costs reflected in the two systems resemble similar overall values, but important differences exist due to the nature of their record keeping, as described below.

OMS contains asset datasets related to maintenance operations, and it is used by the Maintenance and Facility Management Division (among others) to "plan and manage budgets, allocate resources including manpower, equipment, and materials, record work done, and analyze maintenance needs" (U.S. Department of Transportation, 2014). Thus, work orders are tracked in OMS and can be consulted to retrieve maintenance costs.

Among our variables of interest, OMS work order reports contain the following information:

- Unique work order number
- Route, MP Start/End (rounded to nearest whole milepost number; this field could also contain empty values)
- Labor and equipment costs
- Materials costs (limited account of this item)
- Work dates
- Activity type (barrier type)
- Work description (open text field with optional description of work performed; this field could also contain empty values)

A total of 26,761 work orders were extracted from OMS in the 10-year span between 2008 and 2018.

Similarly, FINET is UDOT's financial accounting system and contains cost records representing the ultimate costs of a project or work order. Based on observations from the data, FINET work order expenses were greater than or equal to the OMS expenses, primarily because they track a more comprehensive set of material expenses, and also because they represent the total amount spent by UDOT for accounting purposes (whether the expense has a similar breakdown to OMS or not).

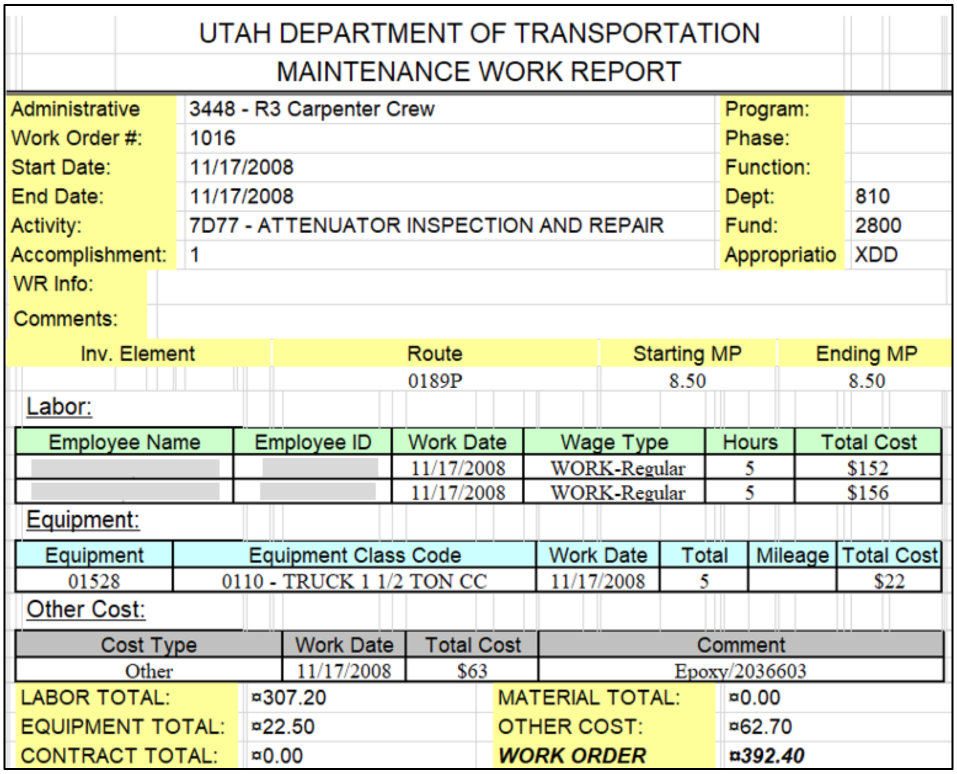
FINET's format for the work order costs was organized as follows:

- Administrative unit
- Activity
- Amount
- Equipment cost
- Labor cost
- Material cost
- Total cost
- Fiscal period and year (month and year)

In addition, FINET transactions also provided information by Administrative Unit and activity, where each record was associated to a transaction document ID for accounting purposes. A line description was also included in the transaction table, and contained information on the work performed. This was initially considered a promising addition to link work order numbers to transaction, particularly because some location details (e.g., route and mileposts) were embedded in the free text, but it was ultimately deemed too sparse and unreliable to create links between OMS and FINET.

Lastly, FINET work order costs and transaction data consolidates reporting per activity code or more aggregate levels (e.g., fiscal year and/or month), which is a deviation from the OMS data tracking individual work orders. Therefore, association of transaction data for a given barrier type (the most general activity code) could be done properly, but not at the level where maintenance work could be linked to a specific roadway or barrier segment.

In an additional effort to explore details within the work orders and potentially uncover clear links between individual work orders and FINET, the team downloaded each work order and compiled a summary of labor, equipment, and materials costs, ensuring that the OMS summary reports were correct, verifying that the costs in OMS were compiled differently in FINET, and that most material costs were completely absent from the work orders but present in FINET. For illustration purposes, a sample work order out of the 2600 work orders extracted is shown in Figure 6.



UTAH DEPARTMENT OF TRANSPORTATION
MAINTENANCE WORK REPORT

Administrative	3448 - R3 Carpenter Crew	Program:	
Work Order #:	1016	Phase:	
Start Date:	11/17/2008	Function:	
End Date:	11/17/2008	Dept:	810
Activity:	7D77 - ATTENUATOR INSPECTION AND REPAIR	Fund:	2800
Accomplishment:	1	Appropriatio	XDD
WR Info:			
Comments:			

Inv. Element	Route	Starting MP	Ending MP
	0189P	8.50	8.50

Labor:

Employee Name	Employee ID	Work Date	Wage Type	Hours	Total Cost
[redacted]	[redacted]	11/17/2008	WORK-Regular	5	$152
[redacted]	[redacted]	11/17/2008	WORK-Regular	5	$156

Equipment:

Equipment	Equipment Class Code	Work Date	Total	Mileage	Total Cost
01528	0110 - TRUCK 1 1/2 TON CC	11/17/2008	5		$22

Other Cost:

Cost Type	Work Date	Total Cost	Comment
Other	11/17/2008	$63	Epoxy/2036603

LABOR TOTAL:	¤307.20	MATERIAL TOTAL:	¤0.00
EQUIPMENT TOTAL:	¤22.50	OTHER COST:	¤62.70
CONTRACT TOTAL:	¤0.00	***WORK ORDER***	***¤392.40***

Figure 6. Sample Individual Work Order from OMS

Overall, manual and automated efforts were combined to extract over 16,570 work order cost reports and over 200,000 transactional records from FINET on maintenance-related costs. After extensive analysis, in comparison to OMS work order data, FINET work order costs and transactions provided the following tradeoffs:

- More complete set of material costs
- Summaries by Administrative Unit and activity per year and month
- No location data or work order number

Thus, FINET records were deemed more appropriate for the maintenance analysis, but it was only available at the large barrier system level (attenuators, cable barrier, concrete barrier, and guardrail). The analysis could not cover much needed details for subcategories of barriers, as it could be done in the previous section in terms of installation.

Regarding the cost differences between OMS work orders and FINET work order costs, two examples are provided next to illustrate cases where they generally differ from each other:

<u>Example 1:</u>

Two work orders are considered in this example for barrier maintenance in the Laketown administrative unit. Table 6 shows the U of U Table with OMS report details.

Table 6. OMS Report Extract for Work Orders - Laketown Administrative Unit

Work Order	Labor Cost	Equipment Cost	Material Cost	Total Cost	Comments
393689	$302.55	$171.00	$0.00	$473.55	Built pad for end treatment.
394322	$135.78	$14.40	$0.00	$150.18	put hazard stickers on and tightened up cables.

Then, a relation between OMS and FINET can be obtained, albeit by month only, from the "RPRT_OMS_FINET_EXP" report accessible to the team, as shown in Table 7. It is noted that had other transactions occurred during the same month, the FINET summaries will differ from the two work orders in OMS.

Table 7. OMS and FINET Report Comparison - Laketown Report from June 2015

Admin Unit	Activity	Cost Completed	Cost Scheduled	Difference (Finet vs. OMS)	Finet Expenditure	Month, Year	Non OMS Expenses	Total Exp (CC + NOE)
1437 – Laketown	7S66 - GUARDRAIL MAINTENANCE (LF - LIN FOOT)	$623.73	$0.00	$19.92	$899.07	2015, 06-June	$255.42	$879.15

The "cost completed" field from FINET equals the total cost from OMS, but the actual expenditures from UDOT also included additional costs from "Non-OMS" expenses. Tracing the documents from individual FINET transactions, the expense for $255.42 was identified as shown in Table 8.

Table 8. FINET Transaction Missing in OMS - Laketown Report from June 2015

Activity	Amount	Month, Year	Line Description	Inferred Description
7S66 - GUARDRAIL MAINTENANCE (LF - LIN FOOT)	255.42	2015, 06-June	016 022024/ cust# UDOT	Gravel from Circle C

So, all costs for the work orders in the example could be traced back to transactions, but the transactions also included $255.42 in costs of material items.

Example 2:

In this example, we consider three work orders from February 2013 in the Salt Lake East administrative unit, as shown in Table 9.

Table 9. OMS Report Extract for Work Orders – Salt Lake East Administrative Unit

WO	Labor Cost	Equipment Cost	Material Cost	Total Cost	Comments
259857	$558.90	$55.00	$0.00	$613.90	clean attenuators
260954	$680.90	$75.60	$0.00	$756.50	washing and cleaning attenuators
260974	$476.80	$63.00	$0.00	$539.80	clean and washing attenuators

The corresponding costs in the FINET work order costs for February 2013 are shown in Table 10 and compared to the OMS records above.

Table 10. OMS and FINET Report Comparison - Salt Lake East from February 2013

Administrative Unit	Activity	Cost Completed	Cost Scheduled	Difference (Finet vs. OMS)	Finet Expenditure	Month, Year	Non-OMS Expenses	Total Exp (CC + NOE)
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	$1,910.20	$0.00	($1,716.60)	$5,107.36	2013, 02-February	$4,913.76	$6,823.9

Similar circumstances apply in this case compared to the previous example. The sum of the "Total Cost" from OMS is the same as the "Cost Completed" value in the OMS_FINET_EXP table. Interestingly, the FINET expenses are lower than the OMS expenses for this circumstance. In this case, there are nearly $5,000 in non-OMS Expenses. However, work order reports and station transactions do not provide a specific description for these expenses, as shown in the transaction details in Table 11.

Table 11. FINET Transactions - Salt Lake East from February 2013

Admin Unit	Activity	Amount	Month, Year	Line Description	Inferred Description
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	4,809.43	2013, 02-February	015 305305/ Correct coding	
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	104.33	2013, 02-February	015 308308/ 14JAN2013 INDUSTRIAL SUPPLY	
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	80	2013, 02-February	Detailed Charge Transaction - Employee/Equipment ID:01992 Usage From/To:02/20/2013 - 02/20/2013	TRUCK/1-1/2 TON/CC/DUMP
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	55	2013, 02-February	Detailed Charge Transaction - Employee/Equipment ID:0214324 Usage From/To:02/13/2013 - 02/13/2013	TRUCK 1 TON DUAL WHL CC
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	33	2013, 02-February	Detailed Charge Transaction - Employee/Equipment ID:0214324 Usage From/To:02/20/2013 - 02/20/2013	TRUCK 1 TON DUAL WHL CC
2425 - Salt Lake East (Metro)	7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	25.6	2013, 02-February	Detailed Charge Transaction - Employee/Equipment ID:19149 Usage From/To:02/20/2013 - 02/20/2013	PICKUP 3/4-T EXT CA

At first, it would appear that there are no expenses for the labor involved on this project in the transaction data. However, the sum of the Labor costs in the OMS orders totals to exactly the difference between the FINET and OMS. This would seem to indicate that the $4,913.76 in non-OMS Expenses includes the labor costs, which might lead us to assume that this unknown cost is actually $3,197.16 after the labor costs are subtracted. The FINET transactions, while broken down differently compared to OMS, still account for all costs and have the potential to provide a more complete picture of total maintenance expenses. Note that different aggregation of costs made the identification of linkages between work orders and transactions unfeasible.

After extensive exploration of the data, the team extracted overall maintenance expenses from the three main sources of data described above: 1) work orders (OMS), 2) work order costs (FINET), and 3) work order transactions (FINET). The consolidation of those efforts resulted in a general breakdown of maintenance costs for the entirety of the reporting period (2008-2018), as shown below in Table 12.

Table 12. Total Maintenance Costs by Barrier Type from OMS and FINET Data

Activity	Work Orders	FINET Work Order Costs	FINET Transactions
	Total Cost	Total Cost	Total Cost
7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	$479,439.17	$1,629,675.81	$1,644,157.54
7S66 - GUARDRAIL MAINTENANCE (LF - LIN FOOT)	$775,811.25	$1,893,089.53	$1,929,321.48
7S70 - CABLE BARRIER (LF - LIN FOOT)	$251,847.18	$625,759.55	$628,979.96
7S71 - CONCRETE BARRIER MAINTENANCE (LF - LIN FOOT)	$740,542.25	$1,518,634.17	$1,562,536.75

Furthermore, compiling the quantities affected by the maintenance activities, a cost per unit of length or for each element (in the case of attenuators), was also obtained with the results shown in Table 13.

Table 13. Unit-Based Maintenance Costs by Barrier Type from OMS and FINET Data

Activity	Units Treated	Work Orders	Work Order Costs	FINET Transactions
		Unit Cost	Unit Cost	Unit Cost
7D77 - ATTENUATOR INSPECTION AND REPAIR (EA - EACH)	5245	$91.41	$310.71	$313.47
7S66 - GUARDRAIL MAINTENANCE (LF - LIN FOOT)	243972	$3.18	$7.76	$7.91
7S70 - CABLE BARRIER (LF - LIN FOOT)	296985	$0.85	$2.11	$2.12
7S71 - CONCRETE BARRIER MAINTENANCE (LF - LIN FOOT)	518807	$1.43	$2.93	$3.01

From the table above, maintenance for attenuators resulted in the highest individual costs per unit, compared to a linear foot of activities for other types of elements, albeit attenuators also differ the most in terms of installation costs, thus making this finding expected. For example, maintenance on a lower cost W-beam flared end treatment is expected to have a much lower cost than for a larger and more expensive self-restoring Type D attenuator. However, further breakdown of attenuator data so that costs could be identified for specific types was not possible from work orders, limiting the maintenance analysis to the larger barrier groups only.

Fortunately, a large number of treated units was gathered for the three remaining barrier groups, as measured per linear-foot, making such estimates and derived metrics more reliable. Statewide.

guardrail maintenance had generally higher unit costs, followed by concrete barriers, and then cable barriers.

Also, note that the type of activities for each barrier type were significantly different. While most concrete barrier maintenance was related to straightening or realignment of the barrier, guardrail and cable barrier maintenance covered a wider range of tasks, like replacing posts or blocks, end terminals, or connecting elements such as bolts.

It is also important to note that an additional maintenance expense category includes activities under the code "7M68 - CONTRACTUAL ATTENUATOR & GUARDRAIL MAINT (STD - Stnd Cst $)" for a total amount of $2,670,157 over the study period. Overall, 857 records were found under this category, for an average cost of $3,322 recorded per work order. Even though these expenses are certainly related to maintenance and they are significant in number, they cannot be broken down into costs per units treated, and thus could not be used in the unit cost estimation for eventual life-cycle costs analysis. However, as mentioned previously, the number of elements treated considered in the calculation of unit costs for Table 13 is large, providing a certain degree of confidence in the calculation.

OTHER PROJECT COSTS AND CRASH-RELATED COSTS

Additional costs not related to planned maintenance were also discussed with the TAC and extracted from project expense summaries for the same analysis period. Information from over 7,200 projects were obtained, totaling over $158.3 million, and included the following key data:

- Project number, date, pin, region, and type (state or federal)
- Item code (including non-standard items with asterisk), unit, and quantities
- Original and adjusted quantities
- Work description
- Amount paid

The team analyzed each project line to classify the data into categories that could be understood more easily. As part of the classification, activity codes and descriptions were created by the team to identify relevant records in relation to specific barrier types and included the following main categories:

- Relocation
- Raise
- Salvage
- Replacement

Separation of these items was done through an analysis of the project data, including free text project notes. This process resulted in new “search keys” that incorporated several item descriptors. The difficulty in this approach was mainly the non-standardized format of the expense descriptions so key words and variations of those were mined from the original text. The components that created the search keys are described as follows:

- Item Type: Described the overall item category at the highest level. Levels included: cable barrier, concrete barrier, crash cushion, end section, guardrail.
- Description: Combination of item type with a secondary category for descriptive purposes. Levels included a total of 41 combinations for all item types, as shown in Table 14.
- Action: Described the type of “other” cost category analyzed. Levels included: Raise, relocate, repair, salvage.
- Item character: Component to describe if the item could be described using standard item codes or required special codes for unique or modified items. Levels included: numeric code (standard items), P code (special item code), asterisk (special item code), any (all codes combined).
- Project type: Indicated if the project cost was part of projects classified as state or federal. Correspondingly, two levels existed for this component, plus one level to combine both cases.

Table 14. Barrier Types and Secondary Classifications for Search Keys

Item Type	Description
Cable Barrier	Cable Attachment Rail
Cable Barrier	Cable Barrier
Cable Barrier	Cable/W-Beam Anchor Assembly
Cable Barrier	End Anchor
Cable Barrier	End Treatment
Cable Barrier	Foundation
Cable Barrier	Line Post
Cable Barrier	Overlap Termination
Cable Barrier	Parapet Anchor Bracket
Cable Barrier	Parapet Departure Bracket
Cable Barrier	Post Sleeve
Cable Barrier	Posts
Cable Barrier	Tension Gauge
Cable Barrier	Terminal
Cable Barrier	Transition
Concrete Barrier	Concrete Barrier
Concrete Barrier	End Section
Concrete Barrier	Half Barrier
Concrete Barrier	Stain
Concrete Barrier	Surface Repair
Concrete Barrier	Terminal
Concrete Barrier	Transition
Crash Cushion	Base and Gutter
Crash Cushion	Crash Cushion
Crash Cushion	Foundation
Crash Cushion	Grading
Crash Cushion	Plastic Nose Piece
Guardrail	Anchor
Guardrail	Bridge Connection Element
Guardrail	Bridge Rail
Guardrail	End Treatment
Guardrail	Guardrail
Guardrail	Guardrail & Cable Attachment Assembly
Guardrail	Offset Block
Guardrail	Plank Repair
Guardrail	Post Holes
Guardrail	Posts
Guardrail	Rub Rail
Guardrail	Terminal
Guardrail	Transition Element
Guardrail	Weathering Steel

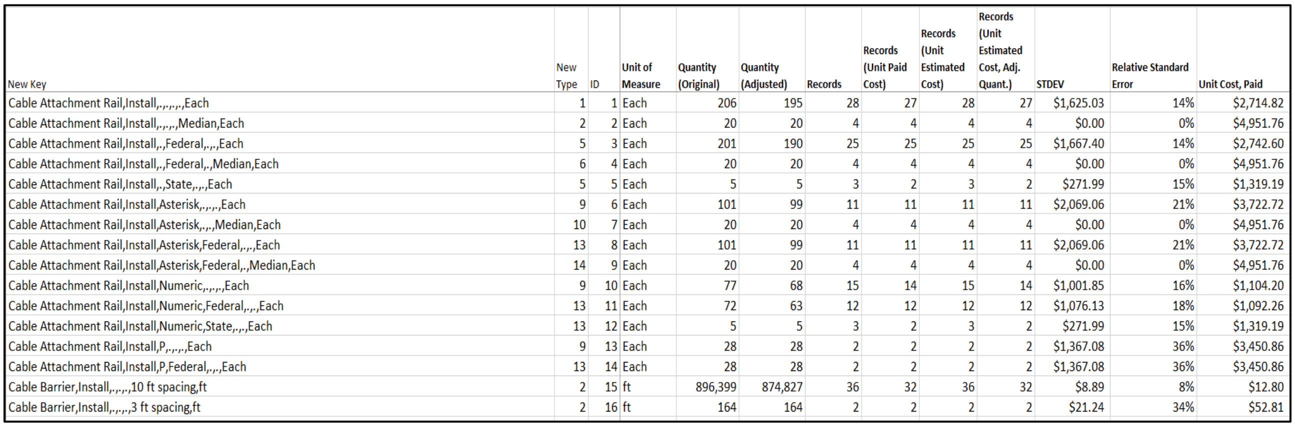
- Material type: For project costs with such description, it indicated construction or material properties. Levels included:

    - For concrete barrier: pre-cast, cast-in-place, unspecified, all types
    - For guardrails: W-beam, unspecified, all types
- Size/Shape: Described an item property related to size, shape, or spacing. Levels included:
    - For cable barrier: 3-ft spacing, 3 or 4 cable system, 5-ft spacing, 10-ft spacing, unspecified, all types.
    - For concrete barrier: constant slope, New Jersey shape, unspecified, all types.
    - For guardrail: curved, median, steel post, wood post, nested, reduced deflection, various spans, unspecified, all types.
    - For attenuators: Type A, Type B, Type C, Type D, Type F, Type G, Type H, EOL, Anchor, Buried, End Section, None, Other, Transition.

The combination of all search key components defined unique identifiers used by the research team in the data re-classification, and in the calculation of separate costs for very specific categories.

This also allowed the team to organize data and group identifiers for aggregate measures, so it was possible to provide high-level statistics and unit costs for larger categories. Table 15 shows, for all items, a summary of the paid unit costs based on modified quantities for each barrier type and each action associated to other expense categories not included under maintenance. Additional tables showing separate summary statistics for all items based on original quantities and also on estimated unit costs from PDBS are included in Appendix 4.

The complete file with over 5,000 different individual and summary classifications and their project-related costs are available from the research team upon request. A sample screenshot of the classifications and the calculated values is shown in Figure 5.



New Key	New Type	ID	Unit of Measure	Quantity (Original)	Quantity (Adjusted)	Records	Records (Unit Paid Cost)	Records (Unit Estimated Cost)	Records (Unit Estimated Cost, Adj. Quant.)	STDEV	Relative Standard Error	Unit Cost, Paid
Cable Attachment Rail,Install,.,.,.,.,Each	1	1	Each	206	195	28	27	28	27	$1,625.03	14%	$2,714.82
Cable Attachment Rail,Install,.,.,.,Median,Each	2	2	Each	20	20	4	4	4	4	$0.00	0%	$4,951.76
Cable Attachment Rail,Install,.,Federal,.,.,Each	5	3	Each	201	190	25	25	25	25	$1,667.40	14%	$2,742.60
Cable Attachment Rail,Install,.,Federal,.,Median,Each	6	4	Each	20	20	4	4	4	4	$0.00	0%	$4,951.76
Cable Attachment Rail,Install,.,State,.,.,Each	5	5	Each	5	5	3	2	3	2	$271.99	15%	$1,319.19
Cable Attachment Rail,Install,Asterisk,.,.,.,Each	9	6	Each	101	99	11	11	11	11	$2,069.06	21%	$3,722.72
Cable Attachment Rail,Install,Asterisk,.,.,Median,Each	10	7	Each	20	20	4	4	4	4	$0.00	0%	$4,951.76
Cable Attachment Rail,Install,Asterisk,Federal,.,.,Each	13	8	Each	101	99	11	11	11	11	$2,069.06	21%	$3,722.72
Cable Attachment Rail,Install,Asterisk,Federal,.,Median,Each	14	9	Each	20	20	4	4	4	4	$0.00	0%	$4,951.76
Cable Attachment Rail,Install,Numeric,.,.,.,Each	9	10	Each	77	68	15	14	15	14	$1,001.85	16%	$1,104.20
Cable Attachment Rail,Install,Numeric,Federal,.,.,Each	13	11	Each	72	63	12	12	12	12	$1,076.13	18%	$1,092.26
Cable Attachment Rail,Install,Numeric,State,.,.,Each	13	12	Each	5	5	3	2	3	2	$271.99	15%	$1,319.19
Cable Attachment Rail,Install,P,.,.,.,Each	9	13	Each	28	28	2	2	2	2	$1,367.08	36%	$3,450.86
Cable Attachment Rail,Install,P,Federal,.,.,Each	13	14	Each	28	28	2	2	2	2	$1,367.08	36%	$3,450.86
Cable Barrier,Install,.,.,.,10 ft spacing,ft	2	15	ft	896,399	874,827	36	32	36	32	$8.89	8%	$12.80
Cable Barrier,Install,.,.,.,3 ft spacing,ft	2	16	ft	164	164	2	2	2	2	$21.24	34%	$52.81

Figure 5. Post-Classification of Project Costs. Complete File Contains over 5,000 New Keys.

Table 15. Paid Initial Unit Costs Based on Adjusted Quantities for Non-Maintenance Actions – All Items

Paid Unit Cost, Adjusted Quantities, All Items

Barrier Type	Action	Unit of Measure	Quantity (Original)	Quantity (Adjusted)	Total Records	Records with Costs	Relative Standard Error	Weighted Average Cost	Average Cost	Median Cost	Interquartile Range
Cable	Relocate	Feet	21,033	21,033	7	7	43%	$12.33	$26.17	$10.90	($9.05 - $28.59)
Cable	Salvage	Feet	45,196	45,196	4	4	24%	$8.69	$16.10	$15.30	($12.31 - $19.09)
Cable	Tension Gauge Applied	Each	18	18	16	15	9%	$2,410.25	$2,419.27	$2,275.00	($2,250.00 - $2,632.00)
Concrete	Relocate	Each	8	8	2	2	47%	$304.68	$468.70	$468.70	($359.35 - $578.05)
Concrete	Relocate	Feet	16,637	16,637	17	14	33%	$6.10	$15.31	$9.94	($5.85 - $13.87)
Concrete	Replace	Feet	95	95	1	1	--	$17.08	$17.08	--	--
Concrete	Salvage	Each	484	484	3	2	71%	$131.48	$81.14	$81.14	($52.19 - $110.10)
Attenuator	Raise	Each	2	2	2	2	40%	$1,786.45	$1,786.45	$1,786.45	($1,433.23 - $2,139.68)
Attenuator	Relocate	Each	36	36	25	22	18%	$3,378.55	$3,398.75	$2,368.14	($1,925.00 - $3,875.00)
Attenuator	Replace	Each	11	11	2	2	52%	$3,000.00	$5,250.00	$5,250.00	($3,875.00 - $6,625.00)
Attenuator	Salvage	Each	11	5	3	1	--	$1,750.00	$1,750.00	$1,750.00	($1,750.00 - $1,750.00)
Guardrail	Raise	Each	9,670	9,742	2	2	34%	$13.29	$11.77	$11.77	($9.79 - $13.75)
Guardrail	Raise	Feet	69,643	69,643	21	18	13%	$2.55	$2.67	$2.34	($1.67 - $3.18)
Guardrail	Repair	Feet	84	84	1	1	--	$19.52	$19.52	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$7.20	$7.20	--	--

Other project costs, such as the ones identified with the new search keys, and also for the more general categories, can be used in a life-cycle cost analysis given the expectation of an event to occur. Engineers familiar with their area of operation can incorporate cycles of project costs in the analysis, so that activities such as raise or repair or relocate can be applied to the cost estimates. Likewise, salvage costs should be applied at the discretion of the engineer and gauged in relation to the item's replacement cost, often equated to new installation costs described in an earlier section.

Crash-Related Costs

A separate significant category initially explored by the research team was related to long-term costs due to motor vehicle crashes. Detailed crash data was available to the team through UTAPS-CDI (Utah's Crash Data Initiative) maintained by the University of Utah, and the team had access to non-recoverable or recoverable costs from crashes from OMS or FINET.

However, work orders, transaction records, and in general cost tracking for barrier repairs related to crashes were not specific enough to associate a given event or even specific barrier types to such expenses. The database had "comments" for each work order, but those were non-standardized and often not descriptive enough, and the location of the repair/maintenance work was approximated to the nearest mile, as opposed to a specific milepost along the linear referencing system. Lastly, since the activity codes for these expenses were limited to indications of "recoverable" or "non-recoverable" expenses, actual repair costs for barrier elements were only identifiable through limited descriptions in the OMS work order, and as described above, most of which would not include material costs.

In practical terms, and in relation to crash-related recoverable costs, a work order may or may have a location specified, or comments describing the type of work performed without separation between barrier or other repairs (or if the work was related to a barrier element), and the date of the maintenance could not be directly related to a specific crash event except for limited cases where the crash case number was identified. Unfortunately, for these reasons, maintenance costs related to crashes were not available for most work orders.

However, crash-related expenses were a significant portion of the total costs associated to barriers. Recoverable plus non-recoverable costs tracked in the OMS records totaled about $6.5 million over the 10-year span including labor, equipment, and limited amounts of material expenses. When incorporating the totality of expenses from these categories and reviewing the FINET transactions, the amount spent on repairs related to crashes resulted in $24.9 million (or 25.4 million after inflation adjustments) over the 10-year analysis period.

Note that this large difference between OMS and FINET was expected given the lack of material expense tracking in OMS, and the significant material usage expected from crash repairs on the barrier systems.

Nonetheless, additional efforts were conducted by the team to provide valuable cost estimates for some of the maintenance activities related to specific barrier systems, as described below.

About 16,000 work order records classified as “Recoverable Accidents” were identified from the complete dataset. Further classification into one of the main barrier types was not readily available, but the team analyzed free text in the work order comments to allow for additional data exploration. This resulted in the identification of a total of 1,990 cable barrier-related work orders, 148 concrete barrier orders, and a combined total of 18 work orders related to guardrail and attenuators.

Concrete barrier work orders related to realignment/straightening of barriers after a crash or an actual replacement of the barrier itself. However, descriptions indicate that a significant portion of these activities were performed through external contractors providing such service, whereas UDOT provided support to assess damages, clean up the site, and other related activities in coordination with law enforcement. This also indicates that actual costs of realigning/straightening or replacing a barrier may not be part of the work orders.

In terms of cable barrier records, the significant number of related work orders were enough to complete more detailed disaggregation to help understand maintenance costs related to crashes. As mentioned above, without material expenses it would be difficult to account for the complete costs incurred, but the team noticed that a few Administrative Units did track material costs, including 133 records in the Beaver unit from 2013 through 2018. These records provide a window into the true costs of repairing cable barrier for a given crash. Table 16 shows summary statistics from the 133 records for key metrics including number of posts replaced (obtained from text descriptions), man hours used, labor costs, equipment costs, material costs, and total costs. Note that the costs are labeled (CPI), so they are adjusted for inflation, as described in the following section.

Table 16. Total Work Order Costs of Repairing Cable Barrier after a Crash

Category	Max	Min	Average	Median
Number of Man Hours Used (hr)	30.00	3.00	10.91	10.00
Post kits or number of posts (Unit)	60.00	1.00	8.93	6.00
Labor Cost CPI ($)	$ 1,008.36	$ 105.42	$ 372.17	$ 341.46
Equipment Cost CPI ($)	$ 108.17	$ 5.66	$ 29.04	$ 21.54
Material Cost CPI ($)	$ 2,383.76	$ -	$ 260.26	$ 121.27
Total Cost CPI($)	$ 3,500.29	$ 171.05	$ 661.47	$ 476.59

In Table 15, costs are provided for work performed after a single crash, and the actual crash record is referenced in the work order form for verification purposes. However, in order to characterize a typical crash and to identify unitary costs that could be used for a life-cycle cost analysis, the team evaluated the repair costs as a function of the number of posts to be replaced, and also the expected number of posts to be damaged if the crash involved a small or a large vehicle. Smaller vehicles included passenger cars, pickup trucks, SUVs and vans or mini vans, whereas large trucks included single unit trucks and larger. Such information was obtained by cross referencing work order records, crash records, and the corresponding vehicle files associated to such crashes. With these two pieces of information, an analysis could identify expected costs for a given length of cable barrier, given its estimated number of crashes over the operational life of the barrier, and if available, using a breakdown of such crashes in terms of vehicle types.

First, Figure 7 shows the distribution of number of cable barrier posts replaced as a function of the vehicle body type. Most crashes involving small vehicles are expected to result in fewer than 10 posts being replaced, whereas larger vehicles tend to have a greater spread of potential damage to the barrier, with 20-30 posts being a common category. It is noted that a total of 375 records from units across the state were used to extract this data.

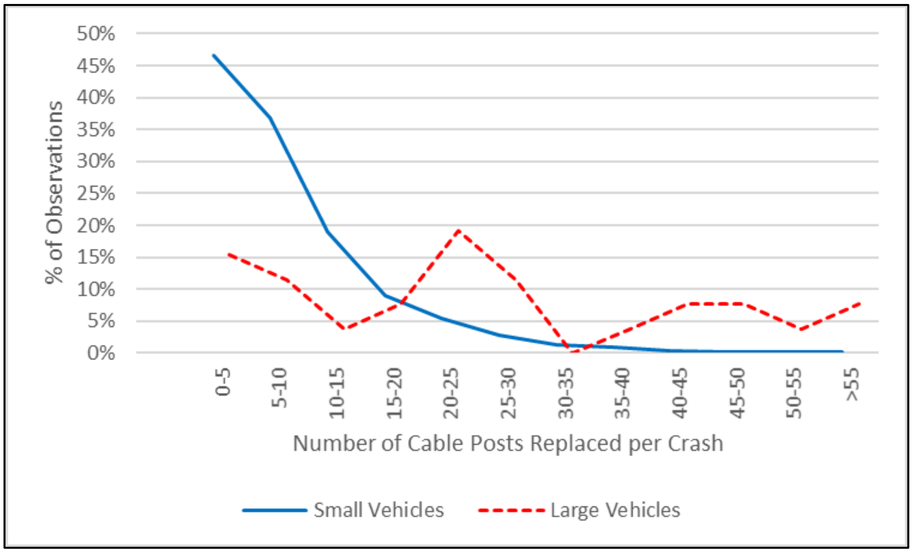


Figure 7. Distribution of Cable Barrier Posts Replaced per Crash - Small and Large Vehicles

Then, the expected costs per repair can be projected if total work order costs can be linked to the number of posts replaced. For this task, the team went back to complete work orders from Beaver and verified that this relationship was consistent. Figure 8 shows that the total work order costs can be well explained by the number of posts repaired ($R^2 = 0.8$), providing a valuable cost estimate in unitary values. This was expected given that the two categories driving the costs in the work orders were labor and materials costs, both of which are directly affected by the number of posts being replaced, whereas equipment values had a smaller and flatter overall participation in total expenses.

On average, given an initial fixed cost of about $223 per work order, the total costs will tend to increase by about $49 per post being replaced (including labor equipment and materials). Thus, for example, a work order for 5 posts is expected to cost about $223 + 5*$49 = $468.

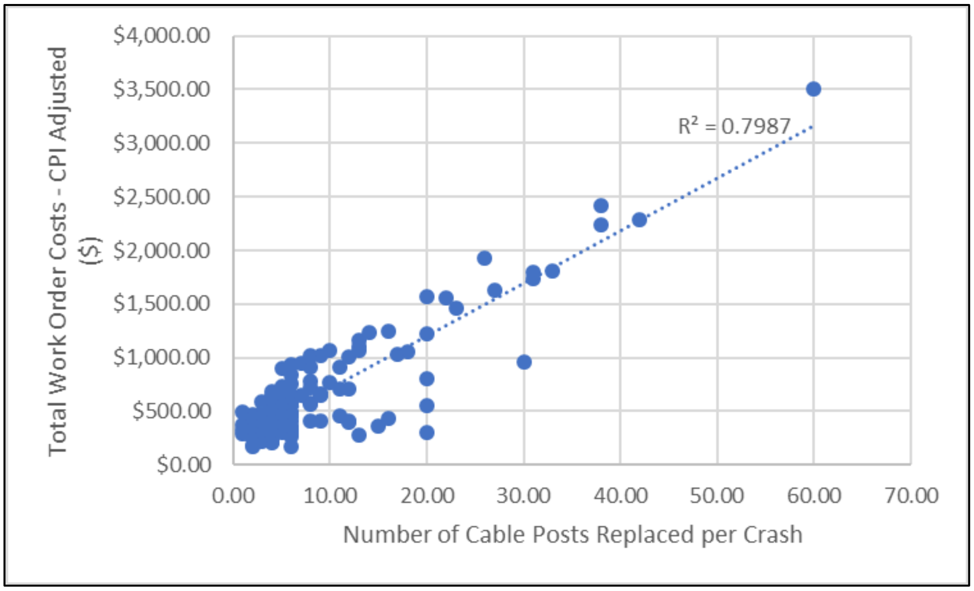


Figure 8. Work Order Costs per Cable Barrier Posts Replaced per Crash

Thus, cable barrier costs due to crash events can be modeled over time, given an expected crash frequency and a composition of vehicle types involved.

Using GIS, the research team also initiated efforts to merge barrier location data with crash data to identify points of interest in space and time, where potential maintenance target points could be flagged for later association with expenses. Crash-to-barrier matches were not straightforward given the overlap of barriers per roadway segment and the fact that different barrier types were present for inner and outer sides of the roadway. This was a common instance as the main routes of interest were divided highways.

After progress meetings with the TAC, and presentations on barriers and crash matching locations, the general suggestion was to keep the focus of the project efforts on big picture life-cycle costs over location-specific cost details. Also, proper identification of UDOT costs would require additional information from significant expenses (both within actual work order documents outside of OMS) and related to maintenance activities which are difficult to narrow down effectively.

ADJUSTMENTS FOR INFLATION

Given that expense reports in this study spanned over a number of years, it was also necessary to provide adjustments to such costs by accounting for effects of inflation. The Consumer Price Index (CPI) was used in place of an assumption made regarding the inflation rate over the study time period, as the CPI should better reflect inflationary effects as opposed to an assumed fixed (e.g., ~2%) inflation rate. In this case, it is used as a measure of inflation over the study time period, converting the summary expenses in the table to representative dollar amounts in 2018 dollars. One potential issue in using the CPI is that the change in costs of consumer goods may not accurately reflect the change in costs for construction materials used by UDOT (both in terms of sourcing methods and bidding prices), leading to potential need for further adjustments.

All values presented in this and later sections in the report have been adjusted based on the CPI. Values for CPI were obtained from historical records made available by the U.S. Bureau of Labor Statistics, which are available on their official website (www.bls.gov). The report used in this study reflects CPI values for all urban consumers (CPI-U) from the U.S. City Average statistics. Factors were calculated every month back from 2018 to 2008. The summarized factors on an annual basis are provided in Table 17 for illustration purposes.

Table 17. Inflationary Adjustment Factors Based on Consumer Price Indices

Year	Adjustment Value
2008	1.166
2009	1.170
2010	1.152
2011	1.116
2012	1.094
2013	1.078
2014	1.061
2015	1.059
2016	1.046
2017	1.024
2018	1.000

With the effects of inflation quantified, analyses from previous sections in terms of installation, maintenance, and other project costs are summarized in this section post-CPI adjustments. Given that disaggregated adjustment factors by month were actually the ones used for the calculations (instead of yearly factors), each cost line was adjusted separately before any new statistical metric was obtained from a collection of records.

The tables in this section and the appendices carry a different format (i.e., black header, and gray and white lines) to further differentiate post-CPI adjustments from original values presented in the sections above (pre-CPI adjustments).

Table 18 contains the most general summary of all costs related to barrier systems, all represented in 2018 dollars. These include PDBS installation costs and FINET total expenses for the remaining cost items. The amount covered in the 10-year span totals $114.2 million, with two thirds of the costs incurred being allocated to installation costs.

Table 18. CPI-Adjusted Summaries of Barrier-Related Expenses by Expense Type

Expense Type	Expenses	Time Period Details
Installation	$76,900,622	Award Date: September 2008 - August 2018
Other Costs (Raise/Relocate/Repair/Salvage)	$1,352,665	Award Date: September 2008 - August 2018
Maintenance	$6,222,556	Document Date: September 2008 - June 2018
Contractual Maintenance	$2,847,270	Document Date: September 2008 - June 2018
Non-Recoverable Crashes	$1,485,799	Document Date: September 2008 - June 2018
Recoverable Crashes	$25,402,960	Document Date: September 2008 - June 2018

In addition, separate new adjusted values for installation, maintenance, and other costs are also illustrated for all items in Tables 19 through 21. Additional tables with separate information for items with and without modifiers, for installation and other project costs, and after adjusting costs for CPI, are shown in Appendix 5.

Table 19. CPI-Adjusted Paid Initial Unit Costs Based on Adjusted Quantities (all items)

Paid Unit Cost, All Items, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	84	10%	$12.73	$25.56	$19.24	($14.43 - $26.28)
Attenuator	Any	Any	Each	4,345	4,218	742	665	5%	$4,859.17	$7,083.82	$3,499.84	($2,852.23 - $8,113.41)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	16	13%	$25,572.02	$30,149.16	$25,996.33	($21,172.81 - $36,714.93)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	65	7%	$20,355.39	$20,764.88	$18,152.31	($15,366.37 - $25,639.40)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	40	7%	$5,369.96	$5,691.07	$4,747.49	($4,473.33 - $6,140.23)
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Each	14	11	8	7	4%	$27,783.07	$27,207.70	$26,635.04	($25,790.15 - $27,878.32)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	90	4%	$9,628.17	$10,159.13	$8,939.33	($8,286.59 - $10,426.10)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	304	3%	$3,345.18	$3,633.07	$3,138.75	($2,834.85 - $3,733.43)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	29	5%	$3,627.50	$3,401.22	$3,114.25	($2,970.83 - $3,534.27)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	110	4%	$2,729.46	$2,999.29	$2,559.26	($2,296.92 - $3,157.61)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	12%	$4,124.70	$3,567.14	$3,483.04	($3,175.72 - $3,916.52)
Concrete	Any	Any	Feet	378,330	373,284	188	161	4%	$46.65	$72.88	$61.51	($50.67 - $85.51)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	20	9%	$72.51	$86.98	$83.57	($70.26 - $92.58)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	130	5%	$46.11	$70.16	$59.01	($49.96 - $79.67)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	12	15%	$90.02	$96.94	$87.74	($70.26 - $110.58)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	6%	$88.08	$79.60	$81.47	($70.26 - $90.03)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		
Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	145	5%	$47.66	$71.64	$59.33	($50.67 - $81.64)
Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	12	13%	$67.05	$91.90	$83.57	($73.53 - $94.40)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	129	5%	$46.10	$69.56	$58.95	($49.89 - $77.62)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	668	3%	$23.90	$34.41	$26.82	($20.31 - $39.89)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	310	6%	$23.47	$30.10	$24.00	($19.45 - $33.83)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	147	6%	$23.77	$32.25	$23.89	($20.00 - $34.25)

Table 20. CPI-Adjusted Paid Initial Unit Costs Based on Adjusted Quantities (all items) for Non-Maintenance Actions

Barrier Type	Action	Unit of Measure	Quantity (Original)	Quantity (Adjusted)	Total Records	Records with Costs	Relative Standard Error	Weighted Average Cost	Average Cost	Median Cost	Interquartile Range
Cable	Relocate	Feet	21,033	21,033	7	7	45%	$13.65	$29.65	$11.75	($9.66 - $31.80)
Cable	Salvage	Feet	45,196	45,196	4	4	23%	$9.24	$16.98	$16.51	($13.06 - $20.43)
Cable	Tension Gauge Applied	Each	18	18	16	15	9%	$2,706.10	$2,720.63	$2,534.08	($2,423.71 - $3,034.39)
Concrete	Relocate	Feet	16,637	16,637	17	14	32%	$6.54	$16.40	$10.71	($6.14 - $15.55)
Concrete	Replace	Feet	95	95	1	1	--	$17.87	$17.87	--	--
Concrete	Reset	Feet	1,718	1,718	6	4	29%	$9.72	$10.99	$10.37	($6.32 - $15.04)
Concrete	Salvage	Each	484	484	3	2	74%	$153.72	$93.70	$93.70	($59.17 - $128.23)
Attenuator	Raise	Each	2	2	2	2	34%	$1,908.94	$1,908.94	$1,908.94	($1,586.52 - $2,231.37)
Attenuator	Relocate	Each	36	36	25	22	18%	$3,627.36	$3,664.19	$2,451.07	($2,112.17 - $4,093.81)
Attenuator	Replace	Each	11	11	2	2	52%	$3,454.71	$6,045.75	$6,045.75	($4,462.34 - $7,629.16)
Attenuator	Salvage	Each	11	5	3	1	--	$1,792.74	$1,792.74	$1,792.74	($1,792.74 - $1,792.74)
Guardrail	Raise	Each	9,670	9,742	2	2	34%	$15.56	$13.78	$13.78	($11.46 - $16.09)
Guardrail	Raise	Feet	69,643	69,643	21	18	13%	$2.64	$2.81	$2.37	($1.75 - $3.28)
Guardrail	Repair	Feet	84	84	1	1	--	$20.43	$20.43	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$8.43	$8.43	--	--

Table 21. CPI-Adjusted Unit-Based Maintenance Costs by Barrier Type from FINET Data

Maintenance Type	Units	Cost (FINET)	Cost, CPI Adjusted (FINET)	Cost (CPI) per Unit
Attenuator (Each)	5,245	$1,629,675.81	$1,748,426.52	$333.35
7M68 - CONTRACTUAL ATTENUATOR & GUARDRAIL MAINT (STD - Stnd Cst $)	857	$2,670,524.39	$2,846,187.99	$3,321.11
Guardrail Barrier (Feet)	243,972	$1,893,089.53	$2,038,840.34	$8.36
Cable Barrier (Feet)	296,985	$625,759.55	$654,749.60	$2.20
Concrete Barrier (Feet)	518,807	$1,518,634.17	$1,639,795.54	$3.16

Adjusted Total Costs

Next, an adjusted breakdown of total costs considering CPI rates by barrier type is provided in Table 22. In the table, the number of installed units represent the total number of length units (feet) or elements (in the case of the attenuators) that had usable records from the databases, and thus would also include records from 2018. This is the reason why, particularly for the cable barrier category, the installed units in 2018 were greater than those inventoried by the end of 2017. Additionally, units for barriers (not attenuators) only account for records where items were purchased by the foot – it doesn't consider units purchased in lump-sums or "each" quantities, as it was described in a portion of the work orders (lump sum items would not be applicable to unit cost analyses for life-cycle cost estimations). Lastly, other costs include the cost to raise, repair, replace, relocate, reset, and salvage barriers.

Table 22. CPI-Adjusted Overall Costs

Barrier Type	Installation Costs	Installation Units	Maintenance Costs	Units Treated	Total Inventoried Units (2017)	Other Costs
Cable Barrier (Feet)	$15,857,172	1,380,955	$654,750	296,985	1,200,641	$730,692
Concrete Barrier (Feet)	$17,027,005	373,284	$1,639,795	518,807	3,975,227	$187,009
Guardrail Barrier (Feet)	$26,217,182	1,261,663	$2,038,840	243,972	2,980,930	$287,128
Attenuator (Each)	$17,799,262	4,218	$1,748,426	5,245	10,073	$147,837
Total	**$76,900,622**		**$6,222,556**			**$1,352,665**

In addition, CPI-adjusted costs per unit were also extracted by cost source, where equipment, labor, and equipment costs were the main cost categories. Figure 9 shows the breakdown for the four main barrier categories. Note that breakdowns are based on maintenance costs, and these do not include recoverable or non-recoverable costs from crashes, which would certainly modify the costs distributions. For example, breakdowns from crash-related costs are illustrated in the previous sections for cable barriers, although they were not available for other barrier types.

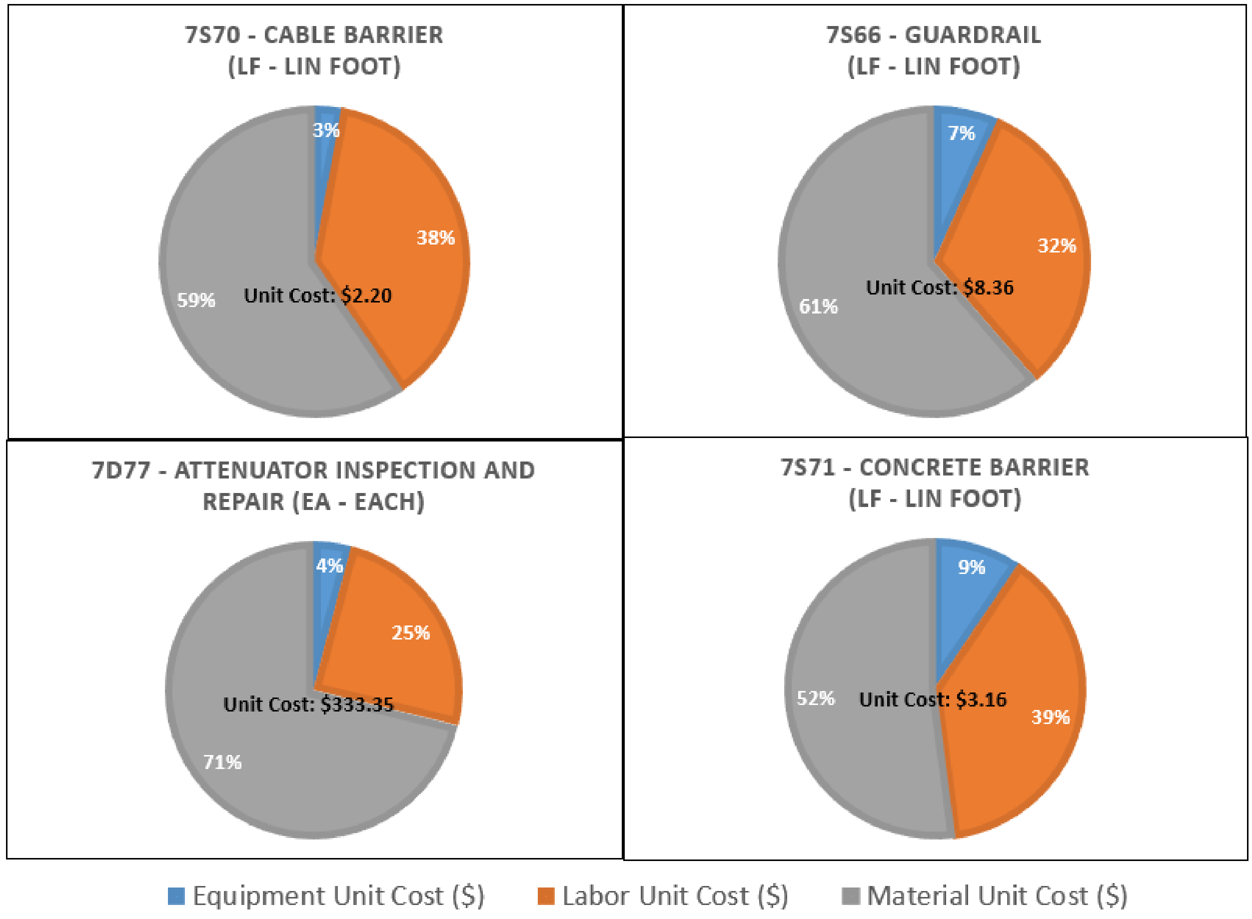


Figure 9. CPI-Adjusted Distribution of Unit Costs by Cost Source for Multiple Barrier Maintenance Activities

LIFE-CYCLE COST ANALYSIS

With a complete set of unitary costs for the main barrier systems, the team proceeded to estimate long-term costs using a standard life-cycle cost analysis (LCCA) framework. In general, the objective of an LCCA is to account for costs associated with an asset over its entire operational life. In this particular case, this exercise will use historic expense categories as a reference, together with a number of assumptions on timelines for such costs to be applied. Ultimately, a unit of length of a barrier system is to be associated to a total cost for the duration of the barrier's operational life span.

LCCA is made under the assumption that the asset under analysis is warranted, so in this case that a particular barrier system is needed. LCCA could inform of overall projected values, providing elements to rate specific barriers from a purely economic standpoint. True comprehensive operational costs derived from actual barrier performance (particularly from crash events) are not calculated in this study, given that work order records proved insufficient to allow matching of maintenance costs to specific crash events. So, additional in-depth safety performance evaluations are needed for true tradeoffs to be leveraged. Approximations of crash-related costs can be made as suggested in previous sections.

Given that only historical costs are known and that projections will be made assuming single-payment capital outlays in the future, an adequate LCCA framework could use a standard expression using present value estimations to account for future inflationary costs, as follows:

$$LCC = C_0 + \left[\sum_{t=1}^{T} \frac{MC}{(1+i)^t} + \sum_{t=1}^{T} \frac{PC}{(1+i)^t}\right] - \sum_{t=1}^{T} \frac{SV}{(1+i)^t}$$

Where,

LCC = Life-cycle cost ($)

C_0 = Installation cost, or investment at time period 0

MC = Maintenance costs for each time period t

PC = Project costs for each time period t

SV = Salvage cost at the end of the operational life

i = Discount rate for future values

T = Operational life span (years)

It is also noted that a single prevailing discount rate (*i*) is used in the equation above, under the assumption that the increase in funding (or the available funds for maintenance and replacement) will be at least equal to the expected rate of inflation.

In order to obtain LCC for each barrier type, a number of input parameters need to be defined first, specifically for decisions related to recurrent costs (maintenance), project costs likely to be incurred, and a service life span to define the operational life of the barrier. The following is a list of such assumptions:

- Discount rate (*i*) = 2% (this fixed rate could be replaced by yearly projections)
- Operational life span:
    - Concrete barrier: 40 years
    - Cable Barrier and guardrail: 30 years
    - Routine maintenance period:
        - Attenuator, concrete barrier, and guardrail: 5 years
        - Cable barrier: 2 years

Unitary costs from the cost analysis above, in their simple average form, were used as inputs for the LCCA framework and are included below in Table 23.

Table 23. Input Values for LCCA Exercise

Barrier Type	**Units**	**Installation (Avg)**		**Maintenance (Avg)**	**Relocation (Avg)**	**Raise (Avg)**	**Salvage (Avg)**	**Replace (Avg)**	**Service Life (yr)**
Attenuator	Each	$4,859.17		$333.35	$3,627.36	$1,908.94	$1,792.74	$3,454.71	20
Guardrail	Feet	$23.90		$8.36		$2.64		$8.43	30
Cable Barrier	Feet	$12.73		$2.20	$13.65		$9.24		30
Concrete Barrier	Feet	$46.65		$3.16	$6.54			$17.87	40

Applying the LCCA formula and projecting costs for the duration of the maximum service life out of the three linear barriers (excluding attenuators), the average cost per year of installing and maintaining a linear foot of guardrail, cable, or concrete barrier is shown in Table 24.

Table 24. Cost per Year in Present Value of Installing and Maintaining Guardrail, Cable, and Concrete Barriers

Metric	**Guardrail**	**Cable Barrier**	**Concrete Barrier**
Expected Cost	$123.45	$76.46	$109.22
Units	Feet	Feet	Feet
Cost/Year	$2.44	$1.47	$2.11

Actual projections from the LCCA are also shown in Figure 10, where the total cumulative costs per barrier type are shown for each barrier type.

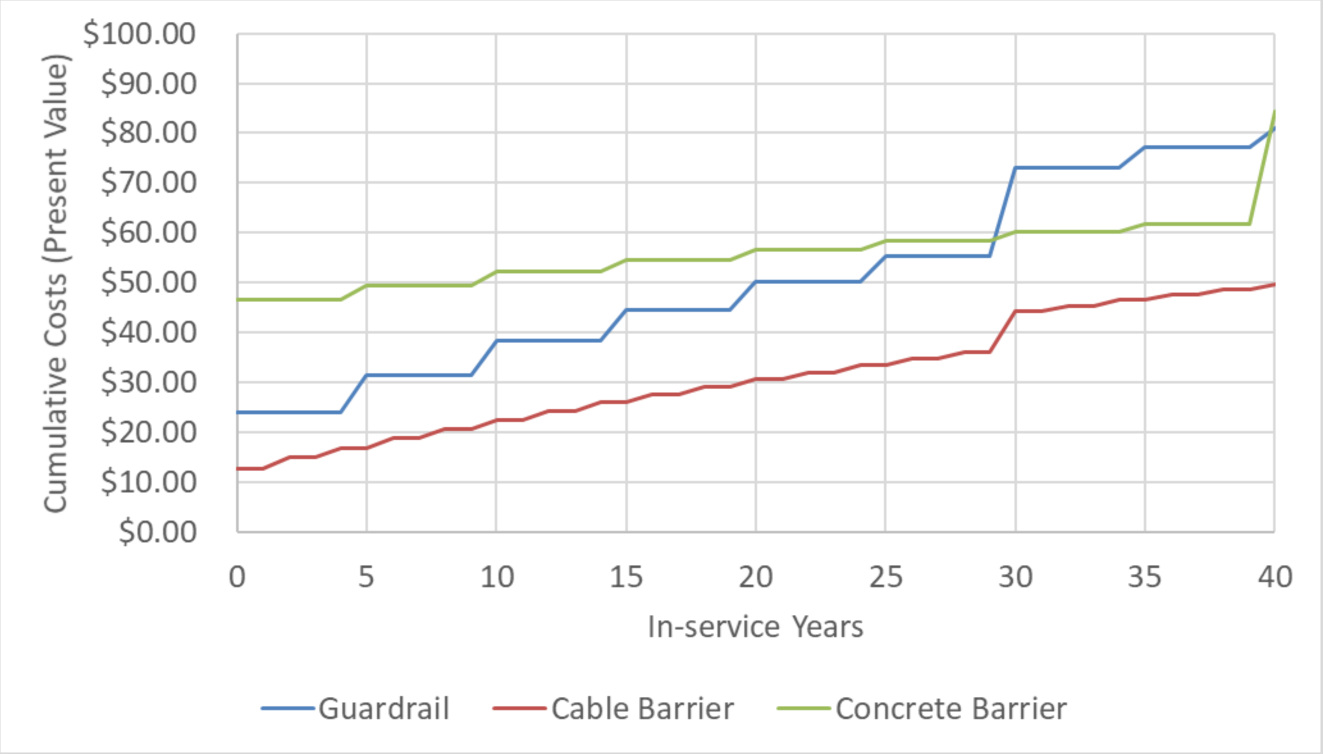


Figure 10. Example Projected In-Service Unitary Costs (per Feet) of Different Barrier Types

CONCLUSIONS AND RECOMMENDATIONS

This research identified priorities to evaluate maintenance and long-term costs associated with roadway systems, and then selected a main topic of interest to further explore operational life costs. In order to accomplish this goal, in Phase I, the team presented the TAC with potential topics for analysis after reviewing published literature, design policies and practice, and conducting a survey of design and maintenance personnel from the Utah DOT and other state DOTs in Federal Region 8. Outcomes from Phase I directed the selection of maintenance costs related to barrier systems to lead the efforts in Phase II.

Barrier-related expense reports covering a 10-year span were obtained from maintenance and financial systems within UDOT. Data included work order reports from the Operations Management System (OMS), and work order costs and transaction records from Utah’s Financial Network System (FINET). All costs were initially explored and classified, and then adjusted for inflation using official historical consumer price indices (CPI).

Initial costs, maintenance costs, and other project costs were identified for different barrier systems, including concrete barriers, cable barriers, guardrails, and attenuators. Disaggregated initial costs were extracted using data transformations and creating new search key phrases to identify subcategories within each barrier type. Subcategories included specific types of barriers within a barrier group such as shape (e.g., attenuator type D or G), size (e.g., 72-in or 84-in posts) or material (e.g., steel or wood), producing a large number of reference costs for very specific items that are expected to be of value as reference for historical expenses.

However, maintenance costs were more general and lacked systematic collection of details on the work performed, allowing for identification of costs but only for each of the major barrier types. As a cost-tracking tool, FINET provided adequate accounting records, but association of those costs to evaluate specific barrier expenses was not a viable option.

Datasets for other project costs included actions applied to barriers such as raise, relocate, repair, or salvage, and such costs were also detailed enough to be allocated not only to major barrier types, but also to subcategories (similar to initial costs). Very detailed project costs for specific barrier items by type, size, material, project type, etc., were produced as part of the study and could also serve as reference historical values.

A separate category included “recoverable” and “non-recoverable” expenses related to general roadway and roadside asset repairs due to motor vehicle crashes. Recoverable expenses were in the order of $25.4 million whereas non-recoverable costs totaled just about $1.5 million. Crash costs lacked details to reliably associate them to barrier-related work as this information was only provided through a free text field that was not always completed. Through manual efforts, unitary costs per crash (but only for cable barrier systems) could be extracted from individual work orders. Crashes were described as a function of the number of posts to be replaced, and the distribution of posts damaged per crash were also obtained. With the information provided, it would be possible to incorporate such costs into a life-cycle cost analysis following an estimation of crash frequency for a given stretch of road.

Overall, barrier-specific costs could be obtained for initial costs, maintenance costs, and other project costs, where maintenance costs were only defined for major barrier type groups. With this information at hand, the unit cost for each expense category was entered into a standard life-cycle cost framework to provide an example on the use of the unit costs.

Unitary costs for different barrier types, including initial costs, maintenance, and other project costs will be valuable to characterize differences in the long-term costs of different barrier systems, particularly for the more specific items in the barrier subcategories (for initial costs and other project costs).

Difficulties with the data processing, and in general for future analysis of maintenance costs, stemmed from the use of non-standardized and/or optional fields in expense reports to characterize the nature of some of the work performed. Recommendations to avoid such limitations in future assessments include the following:

- Addition of standardized descriptions of the asset subject to the work (ideally through a unique inventory number) and the nature of the work itself beyond general activity codes could open important opportunities for systematic maintenance cost tracking and optimization of resources for such activities in the future.

- Association of work order numbers from OMS with financial expenses in FINET's work order costs and transactions will also enhance opportunities for ease of expense tracking back to a specific item, not only back to an activity code. The FINET transactions provided to the team did not contain work order numbers.

- Alternatively, in lieu of fully inventoried assets, and to improve the exact location of the work performed, the use of coordinates in addition (and maybe in replacement of) to mileposts could also benefit asset identification. Linear measurements present limitations for long-term identification of assets and maintenance as they tend to change over time, and they are also difficult to acquire accurately in the field (locations away from physical milepost markers are not typically measured by field crews for linear measurements). Current practice to identify location data by whole mile markers or full one-mile stretches of road may be adequate for some assets, e.g., bridges, but it is not enough for proper identification of barrier system elements.

For all crashes, it is highly recommended to standardize the use of a unique identification number or QR code in the field to mark assets damaged by a specific crash. The team has followed the process that UDOT Station 2444 in Region 2 uses to associate repairs with actual crash records using the crash public safety case number, with the final objective to file insurance claims for expense recovery. In addition to access to properly-located crash events, the Station cited the need for officers to mark the damaged asset with a unique identifier so the crash event, repairs, and the asset can all be linked for the recovery process. Currently, officers may elect to use a sticker to mark the asset with an “A-series” number, but unfortunately this practice is not followed for all crashes. Widespread use of this practice and adequate logging of such unique identifiers (a number or a QR code) will not only help tracking expenses for long-term maintenance analysis, but also to increase UDOT’s cost recovery through insurance claims. This initiative is also expected to have a high benefit-cost ratio for the agency.

Additional work to conduct performance analysis of barrier systems with a strong safety component could also lead to findings on actual costs derived from typified crashes (e.g., by crash type and severity) and corresponding user costs such as property damages and productivity/life-loss costs. Then, asset and user costs could be projected over time over an area given the probability of crash events in space and time. In-service analyses performed routinely by UDOT could be used for this purpose.

Alternative items in the priority list from the TAC could also be further explored using similar financial system reports as the ones described in this report. However, similar pitfalls would be encountered at finer levels of detail when specific assets subject to maintenance work need to be identified. This is expected to apply to drainage elements, cross-section elements and temporary traffic control, and intersection and interchange form and design. The recommendations above could help in addressing these limitations. Also, new data sources and extraction tools emerging from the digitization of asset management in the last few years could open opportunities for more detailed analysis and comprehensive monitoring of maintenance costs over time.

REFERENCES

AASHTO. (2011). A Policy on Geometric Design of Highways and Streets, 6th Edition

Adams, T., & Kang, M. (2006). *Considerations for Establishing a Pavement Preservation Program.* Washington D.C.: Transportation Research Board 85th Annual Meeting.

Arizona DOT. (2012). *Roadway Design Guidelines*

ASCE, & Eno. (2014). *Maximizing the Value of Investments Using Life Cycle Cost Analysis.* Reston, Virginia: American Society of Civil Engineers.

Berry, D. J. (2013). *Value Engineering and Transportation Projects.* Retrieved from meadhunt: http://www.meadhunt.com/insights/transpo/ve-for-transportation/

California DOT. (2014). *Highway Design Manual*

CE. (2006). *Constructing Excellence.* Retrieved from Business Benefits for Whole Life Costing: http://constructingexcellence.org.uk/resources/whole-life-costing/

Ceran, T., & Newman, R. B. (1992). *NCHRP Report 349: Maintenance Considerations in Highway Design.* Washington D.C.: Transportation Research Board, National Research Council.

Clark, J. A. (1999). *Value Engineering Workbook: For Small Transportation Projects.* Worcester Polytechnic Institute. Retrieved from http://www.wpi.edu/Pubs/ETD/Available/etd-0328100-143613/unrestricted/clarkworkbook.pdf

Colorado DOT. (2011). *Roadway Design Guide*

Committee, T. (2014). *Snow and Ice Databook 2014: Winter Maintenance.* Andorra: XIVth International Winter Maintenance Congress.

Dallas, M. (2006). *Value and Risk Management: A Guide to Best Practice.* UK: Blackwell.

Doctor, M. (2014). *Risk-Based Approaches to Highway Design: Achieving Flexibility and Implementing Context Sensitive Solutions.* Washington D.C.: TRB Geometric Design Committee.

FFC. (2001). *A Guide to Integrating Value Engineering, Life-Cycle Costing, and Sustainable Development.* Washington D.C.: National Academy Press.

FHWA. (2002). *Life-Cycle Cost Analysis Primer: Office of Asset Management.* Washington D.C.: U.S. Department of Transportation, Federal Highway Administration.

FHWA. (2014). *Value Engineering Final Rule.* Retrieved from U.S. Department of Transportation, Federal Highway Administration: http://www.fhwa.dot.gov/ve/

FHWA. (2015). *Federal-aid Value Engineering Summary Reports.* Retrieved from U.S. Department of Transportation, Federal Highway Administration: http://www.fhwa.dot.gov/ve/vereport.cfm

Florida DOT. (2013). *Plans Preparation Manual, Vol. 1: Design Criteria and Process*

Freer-Hewish, R. J. (1986). How design, construction and maintenance inter-relationship affect total life performance of roads. *15th ARRB Conference, part 3,* (pp. 293-313).

Greenroads, M. (2015, April). *Project Requirements.* Retrieved from Greenroads Manual v1.5:

Indiana DOT. (2010). *Road Design Manual*

Karim, H., & Magnusson, R. (2008). *Road Design for Future Maintenance Problems and Possibilities*. Journal of Transportation Engineering, Vol. 134, No. 12, 2008, pp. 523-531

Karim, H. (2011). Road Design for Future Maintenance: Life-Cycle Cost Analyses for Road Barriers. Stockholm, Sweden.

Langston, C. (2002). *Design and Construction: Building in Value.* Oxford: Butterworth-Heinemann.

Minnesota DOT. (2012). *Road Design Manual*

Nevada DOT. (2010). *Road Design Guide*

New York State DOT. *Highway Design Manual*

Olsson, U. (1983). *Infrastructure Design with Regard to Maintenance and Operation.* Stockholm, Sweden: Report no: 1983:25, Construction Research Council.

Oregon DOT. (2012). *Highway Design Manual*

Parker, D. (1977). *Value Engineering Theory, Lecture Outline and Reading Supplement, 3rd Edition.* Washington D.C.: The Lawrence D. Miles Value Foundation.

Prarche, S. (2007). Infrastructure Management and the Use of Public Private Partnerships. *CSCE Annual General Meeting and Conference.* Canada: Yellowknife.

Rangaraju, P., & et. al. (2014). *Life Cycle Cost Analysis for Pavement Type Selection.* Clemson: South Carolina Department of Transportation, Clemson University. Retrieved from http://www.clemson.edu/t3s/scdot/pdf/projects/SPR656Final.pdf

Services, V. (2015). *Value Adding Solutions.* Retrieved from VM Services (Pty) Ltd: http://www.vmservices.co.za/pages/value-engineering-benefits

South Dakota DOT. *Road Design Manual*

Stenbeck, T. (2004). *Incentives to Innovations in Road and Rail Maintenance.* Stockholm, Sweden: Royal Institute of Technology.

Thorsman, H., & Magnusson, Y. (2004). *Thorsman and Magnusson Project 04: Collision-free roads.* Sweden: Dalarna University.

Turner, O., & Reark, R. (1981). *NCHRP Synthesis of Highway Practice 78:Value Engineering in Preconstruction and Construction.* Washington D.C.: Transportation Research Board, National Research Council.

TXDOT. (2014). *Roadway Design Manual: Maintenance Considerations in Design.* Texas Department of Transportation.

University, S. (2005). *Guidelines for Life Cycle Cost Analysis.* Stanford, California: Stanford University: Land and Buildings.

U.S. Department of Transportation (2014). “Collection and use of roadway asset data un Utah” FHWA-SA-14-078. URL: https://safety.fhwa.dot.gov/rsdp/downloads/utahiidarcasestudy.pdf

Utah DOT. (2015). *Project Delivery Network*

Walls III, J., & Smith, M. R. (1998). *Life-Cycle Cost Analysis in Pavement Design: In Search of Better Investment Decisions.* Washington D.C.: U.S. Department of Transportation, Federal Highway Administration.

Williamson, A., & et. al. (2010). The Consideration of Maintenance Issues During the Design Process in the UK Public Sector. *Procs 26th Annual ARCOM Conference* (pp. 1091-1100). Leeds, UK: Association of Researchers in Construction Management.

Wilson, D. C. (2005). *NCHRP Synthesis 352, Value Engineering Applications in Transportation: A Synthesis of Highway Practice.* Washington D.C.: Transportation Research Board.

Woodward, D. (1997). Life Cycle Costing-theory, information acqusition and application. *International Journal of Project Management*, 335-344.

Washington State DOT. (2014). *WSDOT Design Manual M 22-01.11*. Retrieved from Chapter 301 Design and Maintenance Coordination: http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/301.pdf

Wyoming DOT. (2015). *Road Design Manual*

APPENDIX 1 - SURVEY QUESTIONNAIRE

Utah Department of Transportation Research Project F-ST99(253)

Incorporating Maintenance Costs and Considerations into Highway Design Decisions

The University of Utah is conducting research for the Utah Department of Transportation to 1) identify how transportation system- and project-level design decisions impact long-term maintenance costs and operations, and 2) recommend possible changes to standard drawings and practice that minimize maintenance costs and optimize maintenance operations while fully considering other operational and safety impacts and trade-offs.

This survey is intended to identify and characterize existing practice for incorporating maintenance costs and other maintenance considerations into highway design decisions. Multiple questions are based on those from a previous effort published as NCHRP Report 349 (1992).

(***Note: "Design" in this survey refers to pavement, bridge, and drainage design as well as roadway geometric design and roadside design***)

1. Does your agency have a process for evaluating the maintainability of highway and street designs, including identifying likely maintenance problems, and communicating needed changes to designers?

   ☐ Yes ☐ No

   If you answered yes to question 1, please answer questions 1a through 1c. If you answered no, please skip to question 2.

   1a) Do you consider this process to be formal or informal?

   1b) Are you able to provide a web URL or any other written documentation of this process?

   1c) Are maintenance personnel involved in the process?

   ☐ Yes ☐ No

   If you answered yes to question 1c, please answer questions 1c-1 and 1c-2. If you answered no, please skip to question 2.

   1c-1) Describe the role of maintenance personnel and the level at which they are involved.

1c-2) At what stage or stages of design are maintenance personnel involved?

2. Do you have any significant maintenance problems resulting from insufficient consideration of maintenance during design, including problems with materials, construction specifications, geometric design decisions, or roadside design/hardware decisions?

   ☐ Yes ☐ No

   If you answered yes to question 2, please answer question 2a. If you answered no, please skip to question 3.

   2a) List the design decisions or details that are causing the most significant maintenance problems.

3. Have more recent "innovative/alternative geometric design alternatives," such as innovative intersection designs, led to any maintenance challenges?

   ☐ Yes ☐ No

   If you answered yes to question 3, please answer question 3a. If you answered no, please skip to question 4.

   3a) List the innovative/alternative geometric design elements that are causing the most significant maintenance problems.

4. Qualitatively describe the weight or importance assigned to the following factors when evaluating alternative highway and street designs (H = high; M = medium; L = low).

1)

Factor	Weight or importance (H = high; M = medium; L = low)
Construction costs	
Traffic operational efficiency and quality of service	
Traffic safety performance	
Operational and maintenance costs (together)	
Maintenance costs (separately)	
Temporary traffic control options and user costs during construction activities	
Temporary traffic control options and user costs during future maintenance activities	
Design costs	
Whether design criteria are met	
Snow storage	
Aesthetics	

4a) List any other factors used to evaluate alternative highway and street designs that were not listed in Question 4 and qualitatively describe the weight or importance in the same way.

Factor	Weight or importance (H = high; M = medium; L = low)

5. Who in your agency makes the evaluations described in questions 4 and 4a?

6. Do designers and maintenance personnel discuss special maintenance needs of past designs that could result in future changes to standard design drawings and design practice?

   ☐ Yes ☐ No

   If you answered yes to question 6, please answer questions 6a and 6b. If you answered no, please skip to question 7.

   6a) How and when do these discussions take place?

   6b) Can you provide at least one example of where these discussions led to an actual change in standard design drawings and practice?

7. List any specific design solutions that you know were primarily developed to alleviate maintenance problems and reduce maintenance costs.

8. Does your agency have a value engineering review process?

   ☐ Yes ☐ No

   If you answered yes to question 8, please answer questions 8a and 8b. If you answered no, please skip to the final page of the survey.

   8a) Are you able to provide a web URL or any other written documentation of this process?

   8b) Are maintenance personnel involved in the process?

   ☐ Yes ☐ No

If you answered yes to question 8b, please answer questions 8b-1. If you answered no, please skip to the final page of the survey.

8b-1) Describe the role of maintenance personnel and the level at which they are involved in your value engineering review process.

Please provide the name and associated information of the person completing this questionnaire:

Name:

Title:

Agency:

Telephone number:

Email address:

Please return the completed survey by September 4, 2015 to:

R.J. Porter

Department of Civil and Environmental Engineering

University of Utah

richard.jon.porter@utah.edu

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

APPENDIX 2 - SUMMARY OF SURVEY RESPONSES

Q1
Does your agency have a process for evaluating the maintainability of highway and street designs, including identifying likely maintenance problems, and communicating needed changes to designers?

- Answered: 31
- Skipped: 0

Answer Choices	**Responses**
Yes	77.42% 24
No	22.58% 7
Total	31

Q2
Do you consider the process for evaluating the maintainability of highway and street designs to be formal or informal?

- Answered: 18
- Skipped: 13

1) Formal
2) Informal
3) There are formal meetings at key points along the design schedule where maintenance personnel bring current issues with the system as well as provide input for new techniques/elements being utilized on the project. There is also a required site visit between maintenance and design.
4) Informal
5) Some of both
6) Both
7) Some formal and some is informal
8) Informal
9) Somewhat formal
10) A little of both
11) Informal
12) Informal
13) Informal
14) Same as before
15) Formal
16) Formal
17) Formal
18) Formal

Q3
Are you able to provide a web URL or any other written documentation of the process for evaluating the maintainability of highway and street designs?

- Answered: 17
- Skipped: 14

1) http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:4131,

2) No

3) http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:4131,

4) Yes

5) UDOT design Process

6) No

7) No

8) No

9) No

10) Can be downloaded here http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:1498,

11) No

12) We have our Maintenance crews participate in design reviews for maintainability

13) N/A

14) http://www.arcgis.com/home/item.html?id=f7fcb6c643b446dca513d532261604d4

15) UDOT's project delivery network

16) No

17) http://www.udot.utah.gov/main/uconowner.gf?n=13674306628756252

Q4
Are maintenance personnel involved in the process for evaluating the maintainability of highway and street designs?

- Answered: 19
- Skipped: 12

Answer Choices	**Responses**
Yes	100.00% 19
No	0.00% 0
Total	19

Q5

Describe the role of maintenance personnel and the level at which they are involved in this evaluation process.

- Answered: 15
- Skipped: 16

1) Maintenance personnel participate in the original concept/kickoff meetings and then they should be a part of each team meeting and milestone review.
2) Maintenance personnel are invited to all milestone meetings during the scoping and design phases. Their input is evaluated and implemented if possible.
3) They are invited to the project meetings and encouraged to bring current issues with the system as well as ideas for modification. They also bring comments concerning existing elements that are problematic.
4) They are invited and encouraged to attend and give input for key design meetings, such as Kick off, scoping and PS&E (Plan, Specification and Estimate)
5) Maintenance is involved at the post-construction meeting.
6) They are invited to all design team meetings.
7) They are asked about any changes they would like to see in projects.
8) Middle and lower level engineers and managers.
9) They provide feedback from their past experience or knowledge of the location of the project.
10) Design reviews from Concept to PS&E
11) Invited and attend design meetings and provide input.
12) Ground level, design meeting level & during construction.
13) Maintenance personnel are asked to attend project team meetings, site visits, and milestone meets. They are asked to provide input on current maintenance issues and the proposed design to help deliver a more maintenance friendly design.
14) We have a roadway management team and there are players there from all groups.
15) Designers complete site visits with maintenance crews, maintenance crews are involved in design reviews.

Q6
At what stage or stages of design are maintenance personnel involved?

- Answered: 15
- Skipped: 16

1) The same answer as question #6.

2) Milestones. Kickoff, scoping, Plan in hand, PS&E meetings.

3) From concept through the project to construction punch list item generation.

4) Those stated in 5 as well as weekly project meetings.

5) Should be at Scoping stage.

6) All the way through.

7) Scoping and plan reviews.

8) Preliminary through to 85% design stage.

9) They are invited to all stages of design from scoping to final plans.

10) Concept to PS&E.

11) Hopefully scoping, but for sure PS&E.

12) From the start. They are involved in every project from the get go.

13) Scoping through advertising.

14) Preconstruction meetings

15) Scoping through PS&E

Q7
What challenges, if any, exist for getting maintenance personnel involved in the process of evaluating the maintainability of highway and street designs? (examples include communication, distance between maintenance sheds and project teams, etc).

- Answered: 15
- Skipped: 16

1) The primary challenge is getting the maintenance staff to attend team meetings and provide meaningful review of milestone plans.
2) They typically do not plan as far ahead in the process and will come to the table too late with ideas or requests.
3) Occasionally, the distance is a challenge but typically if station personnel are not available they have sent comments to their area supervisor or the maintenance engineer to present during the meeting.
4) The information presented is usually foreign to them. They don't understand it very well. They do better with a one on one meetings in the field to point out maintenance concerns.
5) Communication is a struggle we are trying to overcome. We get invitations out, some come some don't, whether that is in person or through email. I think some training for maintenance supervisors and employees could be provided on what they need to address and look at during the scoping meetings.
6) Getting the feedback at the right time. Sometimes feedback comes late.
7) Distance from the designers, communication, and understanding the process.
8) Those shown above plus time availability and priorities.
9) Communication, distance, scheduling ahead to review the plans and have their comments ready, education on how to review plans.
10) They don't always speak their minds.
11) Sometimes input cannot be used. Not all of the meeting applies to them.
12) Ability to hire enough maintenance personnel...when the Utah legislature is following the principles of ALEC...privatize everything.
13) Having them attend the design team meetings.
14) Funding for improvements is the top problem.
15) Ability to get plans to them, communication, getting maintenance to feel involved in design instead of the design being forced on them.

Q8
Do you have any significant maintenance problems resulting from insufficient consideration of maintenance during design, including problems with materials, construction specifications, geometric design decisions, or roadside design/hardware decisions?

- Answered: 23
- Skipped: 8

Answer Choices	**Responses**
Yes	65.22% 15
No	34.78% 8
Total	23

Q9
List the design decisions or details that are causing the most significant maintenance problems.

- Answered: 13
- Skipped: 18

1) The lack of identifying soft spots in pavement is the primary challenge.

2) The tapered end section for median curbing. Though working with the design team, an additional detail is being added to all projects with median curbing to address the issue. The change has not been made to the standard drawing at this time but is in the process.

3) Drainage, signage, slopes.

4) Drainage designs that don't work or can't be maintained, poor pavement quality.

5) Bridge approaches.

6) Enough shouldering material supplied, signs overhanging the road so plow trucks may hit them, sub-standard barrier, signs, guardrail etc. left in projects due to limitations with funding.

7) Snow storage.

8) Inadequate access to roadway or roadside elements for maintenance. Such as inadequate inside shoulder width next to a median wall. Decorative fencing or other design elements for which replacement parts are difficult to obtain. Inadequate snow storage space.

9) Poor shoulder treatments that require constant dressing.

10) Not enough funding to include all maintenance needs.

11) Assumed there are issues, no specifics.

12) Most the problems are from projects already done.

13) Guardrail, pavement designs.

Q10
Have more recent “innovative/alternative geometric design alternatives,” such as innovative intersection designs, led to any maintenance challenges?

- Answered: 23
- Skipped: 8

Answer Choices	**Responses**
Yes	65.22% 15
No	34.78% 8
Total	23

Q11
List the innovative/alternative geometric design elements that are causing the most significant maintenance problems.

- Answered: 12
- Skipped: 19

1) Snow removal and storage has been complicated by some of the innovative interchange designs such as DDIs.

2) Snow plowing in highly channelized intersections is difficult.

3) The CFI has not caused problems but created a few challenges for snow plow operations.

4) One I’m familiar with is tighter turn radius on intersections is a problem for striping trucks.

5) Snow removal.

6) Thru turns are difficult to plow and maintain, there is no place to place snow if there are bike lanes in the shoulders, minimizing right of way crowds areas with signs that can be hit. DDI's because any work in the intersections, shuts down many lanes.

7) Texas U-turns, thru left turns like on Bangerter Hwy, diverging diamond interchanges.

8) Snow removal.

9) Continuous flow intersections make it a challenge to remove snow. Our guys have found solutions to this, but the workaround isn't necessarily safe. Also, DDIs and CFIs require complex pavement markings and signing, and significantly more of them. Pavement marking stencils aren't readily available for the required markings, for example.

10) The barriers along I-15 keep all of the trash on the freeway and require constant cleaning and sweeping.

11) Issues with snow removal.

12) DDI's where to plow off the snow to. Islands when snow plowing if snow depth is deep. Cannot see islands.

Q12
Qualitatively describe the weight or importance assigned to the following factors when evaluating alternative highway and street designs (H = high; M = medium; L = low).

- Answered: 21
- Skipped: 10

	High	**Medium**	**Low**
Construction costs	42.86% 9	52.38% 11	4.76% 1
Traffic operational efficiency and quality of service	85.71% 18	9.52% 2	4.76% 1
Traffic safety performance	80.95% 17	19.05% 4	0.00% 0
Operational and maintenance costs (together)	9.52% 2	57.14% 12	33.33% 7
Maintenance costs (separately)	14.29% 3	33.33% 7	52.38% 11
Temporary traffic control options and user costs during construction activities	42.86% 9	42.86% 9	14.29% 3
Temporary traffic control options and user costs during future maintenance activities	4.76% 1	33.33% 7	61.90% 13
Design costs	23.81% 5	38.10% 8	38.10% 8
Whether design criteria are met	85.71% 18	14.29% 3	0.00% 0
Snow removal/storage	19.05% 4	42.86% 9	38.10% 8
Aesthetics	4.76% 1	57.14% 12	38.10% 8
Ease of access for maintenance personnel and equipment to roadway/roadside features	14.29% 3	28.57% 6	57.14% 12
Availability of replacement/repair parts for roadside hardware	14.29% 3	33.33% 7	52.38% 11
Impact to local businesses	52.38% 11	47.62% 10	0.00% 0

Q13
List any other factors used to evaluate alternative highway and street designs that were not listed in the above Question according to the qualitative weight/importance assigned to those factors?

- Answered: 1
- Skipped: 30

Answer Choices	Responses
High	100.00% 1
Medium	100.00% 1
Low	0.00% 0

Q14
Who in your agency makes the evaluations described in the above two questions?

- Answered: 19
- Skipped: 12

1) Project team.
2) Districts engineers.
3) The entire Team.
4) The project team.
5) Region Staff, Designers and Project Managers.
6) Project Manager, Traffic and Safety Group.
7) Design.
8) Design team.
9) Design Team.
10) Project Manager, UDOT Leadership.
11) Collaborate effort between the field and Road Design.
12) Asset Management Team.
13) Design.
14) Design Division.
15) Project managers and designers.
16) PM and Design team.
17) Deputy Director of Engineering.
18) The design team as a whole.
19) Design Manager.

Q15
Do designers and maintenance personnel discuss special maintenance needs of past designs that could result in future changes to standard design drawings and design practice?

- Answered: 22
- Skipped: 9

Answer Choices	**Responses**
Yes	72.73% 16
No	27.27% 6
Total	22

Q16
How and when do these discussions regarding the special maintenance needs of past designs take place?

- Answered: 13
- Skipped: 18

1) At the initial site visit or during team meetings.
2) During the initial stages of design.
3) When applicable.
4) Hopefully early in the Design phase.
5) During Scoping meeting.
6) After construction of past project and during the design of new ones.
7) Periodically.
8) Seldom.
9) Plan in hand.
10) During design reviews.
11) This is usually pretty informal. If an issue bothers someone in maintenance enough, that person might track down the owner of the standard drawing in question and voice his concerns.
12) Final walkthrough or station inspections.
13) After the fact.

Q17
What is the process used to implement the results of these discussions between designers and maintenance personnel on future designs?

- Answered: 12
- Skipped: 19

1) Comment resolution form is used to document issues and the resolution of the issues.
2) The designer meets with the maintenance personnel to discuss potential issues and ways to reduce issues.
3) If it is a modification to an existing standard drawing there is a specific process to follow. Until a new standard drawing can be implemented then project specific details are used.
4) When a project is due on a road segment.
5) In person and past experience of a person.
6) None.
7) Specification and operational changes.
8) Funding priorities to use the money on pavement trumps.
9) You sly not.
10) Review Comment resolutions.
11) No formal process.
12) Not sure.

Q18
Can you provide at least one example of where these discussions led to an actual change in standard design drawings and practice?

- Answered: 12
- Skipped: 19

1) Change to the rumble strip standard drawings.
2) Culvert End Sections.
3) Adding an additional expansion joint between the median curbing and plowable end sections. This is currently in the process to modify the standard but until then a detail is being added to all projects needing those elements.
4) No specifics come to mind.
5) No.
6) No.
7) Specification developed to recess pavement markings below road surface.
8) No.
9) No.
10) Not a change but more of a focus on including maintenance items in the contract.
11) I don't know of any, but I'm sure there are some examples.
12) No.

Q19
List any specific design solutions that you know were primarily developed to alleviate maintenance problems and reduce maintenance costs.

- Answered: 15
- Skipped: 16

1) Area behind barrier on cut slopes.

2) Cable barrier, grooved in paint, replaceable delineators.

3) Switching from W-Beam barrier to Cast-in-Place or precast concrete barrier.

4) None that I developed. I worked with maintenance and design to get the added expansion joint discussed previously.

5) No specifics come to mind.

6) Installing concrete barrier vs. guardrail where people consistently runoff the road.

7) None.

8) See 17 above.

9) None.

10) None come to mind at this time.

11) I'm at a loss.

12) Slip base signs.

13) Using Guardrail or Cable Barrier to allow debris to blow through and off the road. This also helps with drifting snow and shadows on the road that may freeze.

14) I am not aware of any.

15) Not sure.

Q20
Does your agency have a value engineering review process?

- Answered: 20
- Skipped: 11

Answer Choices	**Responses**
Yes	90.00% 18
No	10.00% 2
Total	20

Q21
Are you able to provide a web URL or any other written documentation of this value engineering review process?

- Answered: 14
- Skipped: 17

1) http://www.udot.utah.gov/main/uconowner.gf?n=94557621849667574

2) http://www.udot.utah.gov/main/uconowner.gf?n=94557621849667574

3) http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:106,

4) No, but Central can provide that.

5) No.

6) No.

7) See content here http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:106,

8) Yes.

9) Our Standard Specifications have a "Value Engineering Incentive" clause.

10) No.

11) No.

12) UDOT web site.

13) No.

14) http://www.udot.utah.gov/main/uconowner.gf?n=94557621849667574

Q22
Are maintenance personnel involved in the value engineering review process?

- Answered: 17
- Skipped: 14

Answer Choices	**Responses**
Yes	29.41% 5
No	70.59% 12
Total	17

Q23
Describe the role of maintenance personnel and the level at which they are involved in your value engineering review process.

- Answered: 5
- Skipped: 26

1) Participate in the VE team.
2) I am not sure at what level however, I believe that are an integral part of the final decision.
3) They, just like all other individuals involved with a project, can suggest and present an idea for a VE.
4) I don't know.
5) Can be included as a team VE Team member, usually at the station Supervisor level.

Q24
Does your agency use innovative contracting methods, such as design-build or contract manager/general contractor (CMGC)?

- Answered: 19
- Skipped: 12

Answer Choices	**Responses**
Yes	94.74% 18
No	5.26% 1
Total	19

Q25
Describe the role of maintenance personnel and the level at which they are involved on projects using these innovative contracting methods.

- Answered: 15
- Skipped: 16

1) Participate on the team.
2) Don't know for sure but I believe they are included.
3) They are involved during the design phase at meetings and during construction they are consulted with if a change or new practices is being implemented.
4) Same as any other project.
5) Depends on the maintenance personnel.
6) None.
7) Not sure.
8) Very minimal.
9) None.
10) N/A.
11) Not much.
12) Maintenance has had much less input on the design build projects but have been involved more in the CMGC Projects.
13) I don't have any experience with this.
14) Don't know.
15) Not involved that I am aware of.

Q26
Have these types of innovative contracting methods led to any maintenance challenges?

- Answered: 16
- Skipped: 15

Answer Choices	Responses
Yes	62.50% 10
No	37.50% 6
Total	16

Q27
List the innovative contracting characteristics that are causing the most significant maintenance problems.

- Answered: 11
- Skipped: 20

1) I am not certain of specific challenges.
2) Maintenance is very low on the priority for these projects, typically maintenance is not even considered.
3) Cannot remember off hand but I believe we have had issues.
4) Placement of ROW elements; fencing, noise walls, and gates, in locations that can cause an access issue or create a future issue of ownership.
5) Drainage.
6) Not sure.
7) Traffic Control, lack of communication throughout process, and if changes are made.
8) Settlement issues ABC (accelerated bridge construction).
9) No practical experience by design.
10) Design Build.
11) Designs meeting minimum requirements.

Q28

Please provide the name and associated information of the person completing this questionnaire:

- Answered: 15
- Skipped: 16

Answer Choices	**Responses**
Name	100.00% 15
Title	100.00% 15
Agency	100.00% 15
Address 2	0.00% 0
City/Town	0.00% 0
State/Province	0.00% 0
ZIP/Postal Code	0.00% 0
Country	0.00% 0
Email Address	100.00% 15
Phone Number	100.00% 15

APPENDIX 3 - INITIAL COSTS FOR ITEMS WITH AND WITHOUT CODE MODIFIERS

Table A-3.1. Paid Initial Unit Costs Based on Original Quantities for Barrier Types - No Code Modifiers

Paid Unit Cost, No Item Code Modifiers												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	50	14%	$11.08	$27.97	$19.98	($13.30 - $26.90)
Attenuator	Any	Any	Each	2,991	2,895	539	487	5%	$4,587.89	$6,769.92	$3,200.00	($2,533.05 - $7,900.00)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	12	17%	$22,261.06	$27,406.59	$23,967.00	($17,442.50 - $33,651.22)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	56	8%	$18,198.16	$18,987.11	$16,586.03	($13,310.68 - $23,300.18)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	30	7%	$4,887.50	$5,372.54	$4,500.00	($4,150.78 - $6,858.04)
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Each	8	8	5	5	2%	$26,319.38	$26,027.00	$26,000.00	($26,000.00 - $26,920.00)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	65	5%	$8,996.78	$9,536.92	$8,500.00	($7,634.00 - $10,000.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	214	4%	$2,896.67	$3,268.80	$2,815.50	($2,506.00 - $3,302.40)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	244	244	33	20	5%	$3,125.06	$3,009.13	$2,925.00	($2,900.00 - $3,293.63)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	82	5%	$2,592.51	$2,723.53	$2,300.00	($2,092.50 - $2,650.70)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	13%	$4,111.76	$3,516.67	$3,400.00	($3,100.00 - $3,875.00)
Concrete	Any	Any	Feet	180,034	175,318	108	92	4%	$50.72	$65.05	$59.35	($46.57 - $75.53)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	5%	$62.01	$75.70	$77.32	($69.89 - $83.12)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	79	5%	$49.17	$62.65	$55.00	($44.82 - $71.96)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	12%	$84.90	$90.85	$83.47	($75.66 - $91.55)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	6%	$84.41	$80.27	$82.76	($73.30 - $84.19)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	86	4%	$50.21	$63.25	$56.01	($46.51 - $74.35)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	7%	$58.91	$72.44	$74.64	($63.41 - $80.31)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	78	5%	$49.15	$61.61	$55.00	($44.70 - $70.91)
Guardrail	Any	Any	Feet	765,320	778,645	523	477	4%	$22.04	$31.89	$24.28	($18.15 - $37.32)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	214	8%	$21.76	$26.89	$20.71	($17.50 - $30.02)
Guardrail	Any	Wood Post	Feet	211,853	204,060	134	124	7%	$21.53	$30.60	$21.97	($18.11 - $34.76)

Table A-3.2. Estimated Unit Costs (from PDBS) for Barrier Types - No Code Modifiers

Estimated Unit Cost (PDBS), No Item Code Modifiers												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	54	6%	$12.03	$20.16	$18.63	($13.61 - $25.38)
Attenuator	Any	Any	Each	2,991	2,895	539	539	4%	$4,202.79	$5,872.70	$3,075.00	($2,550.00 - $7,632.00)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	14	9%	$18,984.38	$21,171.53	$22,063.36	($18,487.50 - $24,595.50)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	61	2%	$15,637.88	$16,181.04	$16,000.00	($14,210.00 - $17,556.49)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	36	3%	$4,395.98	$4,467.21	$4,385.00	($4,125.00 - $4,541.25)
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Each	8	8	5	5	2%	$26,319.38	$26,027.00	$26,000.00	($26,000.00 - $26,920.00)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	71	2%	$8,288.42	$8,373.09	$8,100.00	($7,662.00 - $8,959.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	227	1%	$2,692.63	$2,870.87	$2,800.00	($2,550.00 - $3,082.50)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	244	244	33	33	3%	$3,259.13	$3,320.63	$3,235.00	($2,900.00 - $3,450.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	87	10%	$2,201.61	$2,493.21	$2,200.00	($2,000.00 - $2,439.42)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	5	11%	$4,284.90	$3,663.49	$3,400.00	($2,947.47 - $4,350.00)
Concrete	Any	Any	Feet	180,034	175,318	108	108	3%	$49.29	$59.72	$54.00	($46.00 - $63.87)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	10%	$62.71	$79.70	$77.50	($65.13 - $83.31)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	95	4%	$47.64	$57.15	$52.48	($45.00 - $60.35)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	14%	$85.01	$104.74	$89.50	($83.31 - $131.31)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	15%	$84.52	$96.94	$85.00	($82.75 - $94.00)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	102	3%	$48.81	$57.07	$53.12	($45.73 - $62.50)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	6%	$59.69	$67.39	$68.00	($56.38 - $77.50)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	94	3%	$47.63	$56.23	$52.24	($45.00 - $60.13)
Guardrail	Any	Any	Feet	765,320	778,645	523	523	2%	$21.22	$27.00	$23.00	($18.96 - $31.00)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	227	2%	$21.42	$23.12	$20.48	($17.90 - $25.59)
Guardrail	Any	Wood Post	Feet	211,853	204,060	134	134	3%	$19.06	$23.07	$20.83	($18.00 - $25.00)

Table A-3.3. Paid Initial Unit Costs Based on Adjusted Quantities for Barrier Types - No Code Modifiers

Paid Unit Cost, Adjusted Quantities, No Item Code Modifiers

Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	49	14%	$11.09	$28.41	$20.00	($13.48 - $27.00)
Attenuator	Any	Any	Each	2,991	2,895	539	485	5%	$4,635.19	$6,584.74	$3,200.00	($2,537.09 - $7,700.00)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	12	18%	$21,333.52	$26,157.26	$22,400.00	($17,202.50 - $29,865.36)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	55	7%	$19,058.89	$18,609.41	$16,500.00	($13,221.35 - $23,600.37)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	29	7%	$5,512.65	$5,497.10	$4,500.00	($4,153.13 - $6,823.33)
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Each	8	8	5	5	2%	$26,319.38	$26,027.00	$26,000.00	($26,000.00 - $26,920.00)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	65	4%	$8,904.98	$9,225.38	$8,500.00	($7,634.00 - $9,750.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	214	4%	$2,898.81	$3,162.85	$2,826.50	($2,506.00 - $3,328.30)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	244	244	33	20	5%	$3,125.06	$3,009.13	$2,925.00	($2,900.00 - $3,293.63)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	82	5%	$2,548.34	$2,675.75	$2,300.00	($2,092.50 - $2,650.70)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	13%	$4,111.76	$3,516.67	$3,400.00	($3,100.00 - $3,875.00)
Concrete	Any	Any	Feet	180,034	175,318	108	92	4%	$51.08	$64.11	$59.35	($46.57 - $74.56)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	6%	$62.32	$77.31	$77.32	($69.89 - $83.12)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	79	4%	$49.53	$61.31	$55.00	($44.82 - $69.91)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	12%	$84.90	$90.85	$83.47	($75.66 - $91.55)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	6%	$84.41	$80.27	$82.76	($73.30 - $84.19)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$143.75	$143.75		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	86	4%	$50.57	$62.25	$56.01	($46.51 - $73.65)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	10%	$59.25	$75.20	$74.64	($63.41 - $80.31)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	78	4%	$49.52	$60.25	$54.50	($44.70 - $67.34)
Guardrail	Any	Any	Feet	765,320	778,645	523	475	3%	$21.41	$30.72	$24.22	($18.12 - $36.00)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	214	3%	$20.63	$24.53	$20.67	($17.44 - $28.73)
Guardrail	Any	Wood Post	Feet	211,853	204,060	134	123	7%	$22.00	$30.00	$21.94	($18.07 - $34.37)

Table A-3.4. Paid Initial Unit Costs Based on Original Quantities for Barrier Types with Code Modifiers

Paid Unit Cost, Asterisk in Item Code												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	663,352	639,842	34	27	8%	$11.88	$15.98	$14.85	($12.43 - $19.40)
Attenuator	Any	Any	Each	160	118	20	16	25%	$2,745.51	$4,832.13	$2,907.50	($2,585.87 - $5,175.00)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$20,979.35	$20,979.35		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,500.00	$4,500.00		
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Lump	1	1	1	1		$30,818.00	$30,818.00		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	3	3%	$7,776.00	$7,680.00	$7,920.00	($7,560.00 - $7,920.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	15%	$1,423.89	$2,453.85	$2,637.50	($2,468.49 - $2,738.75)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	1		$3,970.00	$3,970.00	$3,970.00	($3,970.00 - $3,970.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	1		$2,900.00	$2,900.00	$2,900.00	($2,900.00 - $2,900.00)
Concrete	Any	Any	Feet	92,137	91,772	18	15	23%	$28.34	$50.03	$48.75	($12.91 - $66.02)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	4	10%	$78.51	$67.27	$66.02	($58.14 - $75.15)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$22.44	$53.44	$48.38	($12.30 - $56.10)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	28%	$74.74	$52.30	$56.84	($43.86 - $65.27)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	13%	$80.53	$65.49	$59.43	($56.84 - $71.11)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	9	32%	$24.19	$55.57	$48.75	($13.10 - $72.61)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	1		$72.61	$72.61	$72.61	($72.61 - $72.61)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$22.44	$53.44	$48.38	($12.30 - $56.10)
Guardrail	Any	Any	Feet	143,319	131,068	65	52	14%	$16.52	$26.47	$20.67	($17.85 - $29.06)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	22	25%	$15.67	$32.38	$20.67	($17.75 - $32.16)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	7	14%	$16.51	$18.74	$18.03	($14.43 - $22.80)

Table A-3.5. Estimated Unit Costs (from PDBS) for Barrier Types with Code Modifiers

Estimated Unit Cost (PDBS), Asterisk in Item Code Modifiers												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	663,352	639,842	34	34	5%	$11.66	$15.53	$14.89	($11.33 - $19.60)
Attenuator	Any	Any	Each	160	118	20	20	22%	$2,885.65	$4,638.87	$2,957.50	($2,585.87 - $5,175.00)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$20,979.35	$20,979.35		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,500.00	$4,500.00		
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Lump	1	1	1	1		$30,818.00	$30,818.00		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	5	24%	$2,575.65	$6,280.00	$7,920.00	($7,200.00 - $7,920.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	15%	$1,475.48	$2,466.75	$2,637.50	($2,468.49 - $2,738.75)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	2	0%	$3,990.36	$3,985.00	$3,985.00	($3,977.50 - $3,992.50)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	2	2%	$2,950.00	$2,950.00	$2,950.00	($2,925.00 - $2,975.00)
Concrete	Any	Any	Feet	92,137	91,772	18	18	16%	$30.85	$59.54	$55.52	($38.47 - $75.47)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	5	12%	$79.46	$77.09	$67.88	($65.55 - $82.50)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	10	27%	$27.82	$56.65	$49.00	($38.47 - $57.04)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	8%	$80.89	$71.89	$72.78	($64.04 - $80.63)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	10%	$80.98	$69.18	$65.55	($62.53 - $74.03)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	12	21%	$29.71	$62.04	$51.24	($42.16 - $70.41)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	2	24%	$75.85	$88.94	$88.94	($78.41 - $99.47)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	10	27%	$27.82	$56.65	$49.00	($38.47 - $57.04)
Guardrail	Any	Any	Feet	143,319	131,068	65	65	6%	$19.53	$26.07	$22.50	($19.25 - $30.00)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	24	12%	$11.73	$23.45	$20.57	($17.98 - $25.10)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	9	9%	$20.22	$23.63	$21.25	($17.90 - $29.08)

Table A-3.6. Paid Initial Unit Costs Based on Adjusted Quantities for Barrier Types with Code Modifiers

Paid Unit Cost, Adjusted Quantities, Asterisk in Item Code Modifiers												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	663,352	639,842	34	27	7%	$11.88	$15.59	$14.89	($12.43 - $18.22)
Attenuator	Any	Any	Each	160	118	20	16	25%	$2,745.51	$4,832.13	$2,907.50	($2,585.87 - $5,175.00)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$20,979.35	$20,979.35		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,500.00	$4,500.00		
Attenuator	Any	D - Polyethylene, Low Maintenance/Self-Restoring	Lump	1	1	1	1		$30,818.00	$30,818.00		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	3	3%	$7,776.00	$7,680.00	$7,920.00	($7,560.00 - $7,920.00)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	15%	$1,423.89	$2,453.85	$2,637.50	($2,468.49 - $2,738.75)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	1		$3,970.00	$3,970.00	$3,970.00	($3,970.00 - $3,970.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	1		$2,900.00	$2,900.00	$2,900.00	($2,900.00 - $2,900.00)
Concrete	Any	Any	Feet	92,137	91,772	18	15	23%	$28.34	$50.03	$48.75	($12.91 - $66.02)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	4	10%	$78.51	$67.27	$66.02	($58.14 - $75.15)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$22.44	$53.44	$48.38	($12.30 - $56.10)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	28%	$74.74	$52.30	$56.84	($43.86 - $65.27)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	13%	$80.53	$65.49	$59.43	($56.84 - $71.11)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	9	32%	$24.19	$55.57	$48.75	($13.10 - $72.61)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	1		$72.61	$72.61	$72.61	($72.61 - $72.61)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$22.44	$53.44	$48.38	($12.30 - $56.10)
Guardrail	Any	Any	Feet	143,319	131,068	65	52	7%	$16.78	$24.06	$21.17	($17.85 - $30.05)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	22	14%	$14.03	$25.63	$21.19	($17.47 - $32.16)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	7	13%	$20.24	$23.21	$19.10	($17.67 - $27.62)

APPENDIX 4 - OTHER PROJECT COSTS FOR ITEMS WITH AND WITHOUT CODE MODIFIERS

Table A-4.1. Paid Initial Unit Costs Based on Original Quantities for Non-Maintenance Actions - All Items

Paid Unit Cost, All Items, No CPI Adjustment

Barrier Type	Action	Unit of Measure	Quantity (Original)	Quantity (Adjusted)	Total Records	Records with Costs	Relative Standard Error	Weighted Average Cost	Average Cost	Median Cost	Interquartile Range
Cable	Relocate	Feet	21,033	21,033	7	7	43%	$12.33	$26.17	$10.90	($9.05 - $28.59)
Cable	Repair	Each	1	1	1	1	--	$10,836.92	$10,836.92	--	--
Cable	Salvage	Feet	45,196	45,196	4	4	24%	$8.69	$16.10	$15.30	($12.31 - $19.09)
Cable	Tension Gauge Applied	Each	18	18	16	15	9%	$2,410.25	$2,419.27	$2,275.00	($2,250.00 - $2,632.00)
Concrete	Relocate	Each	8	8	2	2	47%	$304.68	$468.70	$468.70	($359.35 - $578.05)
Concrete	Relocate	Feet	16,637	16,637	17	14	33%	$6.10	$15.31	$9.94	($5.85 - $13.87)
Concrete	Replace	Feet	95	95	1	1	--	$17.08	$17.08	--	--
Concrete	Salvage	Each	484	484	3	2	71%	$131.48	$81.14	$81.14	($52.19 - $110.10)
Attenuator	Raise	Each	2	2	2	2	40%	$1,786.45	$1,786.45	$1,786.45	($1,433.23 - $2,139.68)
Attenuator	Relocate	Each	36	36	25	22	18%	$3,378.55	$3,398.75	$2,368.14	($1,925.00 - $3,875.00)
Attenuator	Replace	Each	11	11	2	2	52%	$3,000.00	$5,250.00	$5,250.00	($3,875.00 - $6,625.00)
Attenuator	Salvage	Each	11	5	3	1	--	$1,750.00	$1,750.00	$1,750.00	($1,750.00 - $1,750.00)
Guardrail	Raise	Each	9,670	9,742	2	2	34%	$13.39	$11.85	$11.85	($9.83 - $13.88)
Guardrail	Raise	Feet	69,643	69,643	21	18	13%	$2.55	$2.67	$2.34	($1.67 - $3.18)
Guardrail	Repair	Feet	84	84	1	1	--	$19.52	$19.52	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$7.20	$7.20	--	--

Table A-4.2. Estimated Unit Costs (from PDBS) for Non-Maintenance Actions – All Items

Estimated Unit Cost (PDBS), All Items, No CPI Adjustment

Barrier Type	**Action**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Relocate	Feet	21,033	21,033	7	7	22%	$10.88	$15.17	$10.82	($8.65 - $19.60)
Cable	Repair	Each	1	1	1	1	--	$10,836.92	$10,836.92	--	--
Cable	Salvage	Feet	45,196	45,196	4	4	26%	$8.04	$13.74	$11.74	($9.78 - $15.69)
Cable	Tension Gauge Applied	Each	18	18	16	16	6%	$2,331.33	$2,305.56	$2,272.50	($2,250.00 - $2,566.00)
Concrete	Relocate	Each	8	8	2	2	47%	$304.68	$468.70	$468.70	($359.35 - $578.05)
Concrete	Relocate	Feet	16,637	16,637	17	17	29%	$6.52	$13.18	$8.40	($6.50 - $14.75)
Concrete	Replace	Feet	95	95	1	1	--	$21.35	$21.35	--	--
Concrete	Salvage	Each	484	484	3	3	41%	$165.28	$124.41	$175.00	($99.12 - $175.00)
Attenuator	Raise	Each	2	2	2	2	40%	$893.23	$893.23	$893.23	($716.61 - $1,069.84)
Attenuator	Relocate	Each	36	36	25	25	14%	$3,096.38	$3,000.94	$2,300.00	($2,000.00 - $3,500.00)
Attenuator	Replace	Each	11	11	2	2	23%	$2,636.36	$3,250.00	$3,250.00	($2,875.00 - $3,625.00)
Attenuator	Salvage	Each	11	5	3	3	65%	$354.23	$765.50	$346.50	($273.25 - $1,048.25)
Guardrail	Raise	Each	9,670	9,742	2	2	0%	$14.75	$14.75	$14.75	($14.75 - $14.75)
Guardrail	Raise	Feet	69,643	69,643	21	21	10%	$2.49	$2.77	$2.40	($2.00 - $3.22)
Guardrail	Repair	Feet	84	84	1	1	--	$20.00	$20.00	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$7.20	$7.20	--	--

APPENDIX 5 - CPI-ADJUSTED COSTS FOR INITIAL COSTS AND OTHER PROJECT COSTS

Table A-5.1. Installation - CPI-Adjusted Initial Paid Unit Costs Based on Original Quantities – No Item Code Modifiers

Paid Unit Cost, No Item Code Modifiers, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	50	14%	$11.78	$29.95	$21.40	($14.61 - $28.41)
Attenuator	Any	Any	Each	2,991	2,895	539	487	5%	$5,003.03	$7,377.69	$3,399.46	($2,771.63 - $8,630.04)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	12	17%	$24,179.55	$29,791.91	$24,970.63	($20,008.55 - $34,949.90)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	56	8%	$19,823.03	$20,741.06	$18,200.71	($15,238.75 - $25,276.18)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	30	7%	$5,410.15	$5,929.46	$4,966.32	($4,588.32 - $7,656.25)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	8	8	5	5	5%	$28,281.30	$27,774.71	$27,202.46	($26,635.04 - $28,554.17)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	65	5%	$9,720.75	$10,374.87	$9,068.87	($8,476.18 - $10,828.44)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	214	4%	$3,171.29	$3,582.75	$3,076.34	($2,773.56 - $3,592.21)
Attenuator	Any	G - W-Beam Tangent End Treatment(MASH)	Each	244	244	33	20	4%	$3,174.29	$3,059.02	$2,996.44	($2,970.83 - $3,353.16)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	82	5%	$2,863.70	$2,978.25	$2,515.46	($2,274.93 - $2,877.40)
Attenuator	Any	H - W-Beam Flared End Treatment(MASH)	Each	26	26	5	3	12%	$4,124.70	$3,567.14	$3,483.04	($3,175.72 - $3,916.52)
Concrete	Any	Any	Feet	180,034	175,318	108	92	4%	$54.00	$69.21	$62.06	($49.98 - $82.00)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	5%	$66.46	$81.06	$83.57	($75.60 - $88.72)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	79	5%	$52.28	$66.44	$59.06	($47.68 - $74.98)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	12%	$91.11	$95.54	$89.32	($79.08 - $96.86)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	6%	$90.64	$85.20	$86.25	($76.69 - $92.39)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	86	4%	$53.44	$67.38	$59.81	($48.92 - $80.80)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	7%	$63.12	$78.10	$81.64	($69.20 - $86.50)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	78	5%	$52.27	$65.40	$58.70	($47.66 - $73.55)
Guardrail	Any	Any	Feet	765,320	778,645	523	477	4%	$23.95	$34.81	$26.20	($20.06 - $40.12)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	214	8%	$23.58	$29.31	$22.83	($19.24 - $31.94)
Guardrail	Any	Wood Post	Feet	211,853	204,060	134	124	7%	$23.60	$33.43	$23.76	($19.96 - $38.14)

Half	Pre-Cast	New Jersey Shape (Half)	Feet	2,797	2,797	10	10	17%	$56.20	$70.19	$58.45	($55.31 - $64.68)

Table A-5.2. Installation - CPI-Adjusted Initial Estimated Unit Costs (PDBS) – No Item Code Modifiers

Estimated Unit Cost (PDBS), No Item Code Modifiers, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	54	6%	$12.72	$21.50	$19.81	($14.86 - $26.60)
Attenuator	Any	Any	Each	2,991	2,895	539	539	4%	$4,565.97	$6,370.68	$3,278.16	($2,809.10 - $8,174.47)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	14	8%	$20,932.74	$23,075.99	$24,729.99	($20,988.9 - $26,221.9)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	61	2%	$16,972.60	$17,575.41	$17,443.12	($15,684.2 - $19,271.6)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	36	3%	$4,838.24	$4,894.43	$4,679.77	($4,421.29 - $5,158.04)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	8	8	5	5	5%	$28,281.30	$27,774.71	$27,202.46	($26,635.0 - $28,554.2)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	71	2%	$8,969.73	$9,070.34	$8,948.00	($8,232.81 - $9,647.18)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	227	1%	$2,947.28	$3,144.17	$3,035.40	($2,809.10 - $3,331.22)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	244	244	33	33	3%	$3,286.76	$3,357.19	$3,249.45	($2,970.83 - $3,531.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	87	10%	$2,432.55	$2,719.35	$2,406.37	($2,239.12 - $2,679.14)
Attenuator	Any	H - W-Beam Flared End Treatment(MASH)	Each	26	26	5	5	10%	$4,293.36	$3,693.78	$3,483.04	($2,947.47 - $4,350.00)
Concrete	Any	Any	Feet	180,034	175,318	108	108	3%	$52.22	$63.01	$57.11	($49.11 - $66.43)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	10%	$67.19	$85.42	$83.44	($69.56 - $88.72)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	95	3%	$50.38	$60.08	$55.60	($48.18 - $64.05)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	14%	$91.24	$110.53	$95.36	($88.40 - $135.03)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	16%	$90.77	$103.18	$92.38	($87.08 - $98.35)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	102	3%	$51.69	$60.22	$56.15	($48.51 - $64.75)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	7%	$63.93	$72.72	$75.91	($59.73 - $83.44)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	94	3%	$50.37	$59.15	$55.24	($48.15 - $63.57)
Guardrail	Any	Any	Feet	765,320	778,645	523	523	2%	$22.97	$29.37	$24.98	($20.74 - $33.56)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	227	2%	$23.19	$25.18	$22.33	($20.02 - $27.69)

Guardrail	Any	Wood Post	Feet	211,853	204,060	134	134	3%	$20.92	$25.16	$22.55	($19.95 - $27.01)
Half	Pre-Cast	New Jersey Shape (Half)	Feet	2,797	2,797	10	10	4%	$55.13	$58.23	$56.28	($54.48 - $60.90)

Table A-5.3. Installation - CPI-Adjusted Initial Paid Unit Costs Based on Adjusted Quantities – No Item Code Modifiers

Paid Unit Cost, Adjusted Quantities, No Item Code Modifiers, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	700,292	675,709	54	49	14%	$11.80	$30.42	$21.41	($14.91 - $28.65)
Attenuator	Any	Any	Each	2,991	2,895	539	485	5%	$5,054.60	$7,174.29	$3,481.39	($2,774.8 - $8,562.59)
Attenuator	Any	A - Reusable, Wide	Each	32	29	14	12	18%	$23,172.07	$28,542.58	$23,947.34	($19,262.1 - $32,297.7)
Attenuator	Any	B - Reusable, Narrow	Each	168	156	61	55	7%	$20,760.61	$20,322.25	$17,861.34	($15,165.7 - $25,397.3)
Attenuator	Any	C - Median W-Beam End Treatment	Each	315	278	36	29	7%	$6,102.14	$6,067.16	$5,150.02	($4,609.91 - $7,617.12)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	8	8	5	5	5%	$28,281.30	$27,774.71	$27,202.46	($26,635.04 - $28,554.17)
Attenuator	Any	F - Concrete End Treatment	Each	216	200	71	65	5%	$9,621.56	$10,028.16	$9,068.87	($8,476.18 - $10,828.44)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	1,385	1,367	227	214	4%	$3,173.63	$3,462.38	$3,081.35	($2,773.56 - $3,625.99)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	244	244	33	20	4%	$3,174.29	$3,059.02	$2,996.44	($2,970.83 - $3,353.16)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	597	587	87	82	5%	$2,814.91	$2,924.57	$2,515.46	($2,274.93 - $2,877.40)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	12%	$4,124.70	$3,567.14	$3,483.04	($3,175.72 - $3,916.52)
Concrete	Any	Any	Feet	180,034	175,318	108	92	4%	$54.38	$68.23	$62.06	($49.98 - $81.55)
Concrete	Any	Constant Slope	Feet	19,660	19,560	12	12	6%	$66.80	$82.76	$83.57	($75.60 - $88.72)
Concrete	Any	New Jersey Shape	Feet	160,354	155,738	95	79	4%	$52.67	$65.03	$58.34	($47.68 - $73.43)
Concrete	Cast-In-Place	Any	Feet	2,409	2,409	6	6	12%	$91.11	$95.54	$89.32	($79.08 - $96.86)
Concrete	Cast-In-Place	Constant Slope	Feet	2,389	2,389	5	5	6%	$90.64	$85.20	$86.25	($76.69 - $92.39)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		
Concrete	Pre-Cast	Any	Feet	177,625	172,909	102	86	4%	$53.83	$66.32	$59.34	($48.92 - $78.70)
Concrete	Pre-Cast	Constant Slope	Feet	17,271	17,171	7	7	10%	$63.49	$81.01	$81.64	($69.20 - $86.50)
Concrete	Pre-Cast	New Jersey Shape	Feet	160,334	155,718	94	78	4%	$52.65	$63.98	$58.30	($47.66 - $72.06)
Guardrail	Any	Any	Feet	765,320	778,645	523	475	3%	$23.26	$33.52	$26.13	($20.09 - $39.78)
Guardrail	Any	Steel Post	Feet	488,603	510,868	227	214	3%	$22.36	$26.75	$22.66	($19.23 - $31.18)

Guardrail	Any	Wood Post	Feet	211,853	204,060	134	123	7%	$24.12	$32.72	$23.63	($20.00 - $37.76)
Half	Pre-Cast	New Jersey Shape (Half)	Feet	2,797	2,797	10	10	17%	$56.20	$70.19	$58.45	($55.31 - $64.68)

Table A-5.3. Installation - CPI-Adjusted Paid Initial Unit Costs Based on Original Quantities – Barrier Types with Code Modifiers

Paid Unit Cost, Asterisk in Item Code, CPI Adjustment

Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	663,352	639,842	34	27	8%	$13.57	$18.19	$17.35	($14.09 - $22.21)
Attenuator	Any	Any	Each	160	118	20	16	24%	$2,985.80	$5,252.97	$3,375.58	($2,797.09 - $5,574.49)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$22,252.90	$22,252.90		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,921.65	$4,921.65		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	3	5%	$8,436.28	$8,285.73	$8,662.11	($8,097.55 - $8,662.11)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	16%	$1,616.81	$2,755.70	$2,863.91	($2,699.79 - $3,153.87)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	1		$4,066.97	$4,066.97	$4,066.97	($4,066.97 - $4,066.97)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	1		$3,394.33	$3,394.33	$3,394.33	($3,394.33 - $3,394.33)
Concrete	Any	Any	Feet	92,137	91,772	18	15	23%	$30.89	$53.62	$53.58	($13.22 - $71.16)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	4	10%	$84.59	$72.28	$71.16	($62.43 - $81.01)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$23.90	$56.98	$52.62	($12.60 - $60.77)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	28%	$80.45	$55.97	$60.80	($46.41 - $70.36)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	14%	$86.74	$70.28	$64.06	($60.80 - $76.65)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	9	31%	$25.79	$59.35	$53.58	($13.42 - $78.26)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	1		$78.26	$78.26	$78.26	($78.26 - $78.26)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$23.90	$56.98	$52.62	($12.60 - $60.77)
Guardrail	Any	Any	Feet	143,319	131,068	65	52	14%	$17.53	$28.41	$22.25	($18.69 - $31.21)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	22	24%	$16.82	$35.01	$22.60	($18.82 - $34.66)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	7	14%	$18.46	$21.05	$19.72	($16.15 - $25.80)

Table A-5.5. Installation - CPI-Adjusted Initial Estimated Unit Costs (PDBS) – Barrier Types with Code Modifiers

Estimated Unit Cost (PDBS), Asterisk in Item Code Modifiers, CPI Adjustment

Barrier Type	Material	Attribute	Unit of Measure	Quantity (Original)	Quantity (Adjusted)	Total Records	Records with Costs	Relative Standard Error	Weighted Average Cost	Average Cost	Median Cost	Interquartile Range
Cable	Any	Any	Feet	663,352	639,842	34	34	5%	$13.29	$17.52	$16.51	($12.74 - $21.88)
Attenuator	Any	Any	Each	160	118	20	20	21%	$3,079.51	$5,024.79	$3,375.58	($2,797.09 - $5,574.49)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$22,252.90	$22,252.90		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,921.65	$4,921.65		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	5	24%	$2,812.60	$6,803.12	$8,662.11	($7,532.99 - $8,662.11)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	15%	$1,676.23	$2,770.55	$2,863.91	($2,699.79 - $3,153.87)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	2	0%	$4,087.82	$4,082.33	$4,082.33	($4,074.65 - $4,090.02)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	2	5%	$3,233.80	$3,233.80	$3,233.80	($3,153.54 - $3,314.07)
Concrete	Any	Any	Feet	92,137	91,772	18	18	16%	$33.23	$62.95	$57.56	($41.32 - $79.76)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	5	11%	$85.40	$82.17	$73.17	($69.53 - $88.93)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	10	27%	$29.13	$59.56	$52.40	($41.32 - $58.06)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	7%	$86.77	$76.14	$75.74	($68.18 - $83.70)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	10%	$87.22	$74.20	$69.53	($66.83 - $79.23)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	12	21%	$31.17	$65.32	$55.08	($43.82 - $75.54)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	2	22%	$81.10	$94.13	$94.13	($83.65 - $104.61)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	10	27%	$29.13	$59.56	$52.40	($41.32 - $58.06)
Guardrail	Any	Any	Feet	143,319	131,068	65	65	6%	$20.59	$27.58	$23.18	($19.98 - $32.04)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	24	13%	$12.60	$25.29	$22.25	($19.23 - $27.16)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	9	9%	$22.47	$25.80	$21.55	($20.95 - $32.09)

Table A-5.6. Installation - CPI-Adjusted Initial Paid Unit Costs Based on Adjusted Quantities – – Barrier Types with Code Modifiers

Paid Unit Cost, Adjusted Quantities, Asterisk in Item Code Modifiers, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	663,352	639,842	34	27	6%	$13.57	$17.77	$17.35	($14.09 - $20.68)
Attenuator	Any	Any	Each	160	118	20	16	24%	$2,985.80	$5,252.97	$3,375.58	($2,797.09 - $5,574.49)
Attenuator	Any	B - Reusable, Narrow	Each	1	1	1	1		$22,252.90	$22,252.90		
Attenuator	Any	C - Median W-Beam End Treatment	Each	11	11	1	1		$4,921.65	$4,921.65		
Attenuator	Any	F - Concrete End Treatment	Each	23	21	5	3	5%	$8,436.28	$8,285.73	$8,662.11	($8,097.55 - $8,662.11)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	64	64	8	8	16%	$1,616.81	$2,755.70	$2,863.91	($2,699.79 - $3,153.87)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	56	18	2	1		$4,066.97	$4,066.97	$4,066.97	($4,066.97 - $4,066.97)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	4	2	2	1		$3,394.33	$3,394.33	$3,394.33	($3,394.33 - $3,394.33)
Concrete	Any	Any	Feet	92,137	91,772	18	15	23%	$30.89	$53.62	$53.58	($13.22 - $71.16)
Concrete	Any	Constant Slope	Feet	6,519	6,154	5	4	10%	$84.59	$72.28	$71.16	($62.43 - $81.01)
Concrete	Any	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$23.90	$56.98	$52.62	($12.60 - $60.77)
Concrete	Cast-In-Place	Any	Feet	5,017	5,017	4	4	28%	$80.45	$55.97	$60.80	($46.41 - $70.36)
Concrete	Cast-In-Place	Constant Slope	Feet	4,589	4,589	3	3	14%	$86.74	$70.28	$64.06	($60.80 - $76.65)
Concrete	Pre-Cast	Any	Feet	49,117	48,752	12	9	31%	$25.79	$59.35	$53.58	($13.42 - $78.26)
Concrete	Pre-Cast	Constant Slope	Feet	1,930	1,565	2	1		$78.26	$78.26	$78.26	($78.26 - $78.26)
Concrete	Pre-Cast	New Jersey Shape	Feet	47,187	47,187	10	8	37%	$23.90	$56.98	$52.62	($12.60 - $60.77)
Guardrail	Any	Any	Feet	143,319	131,068	65	52	8%	$17.81	$25.91	$22.60	($18.69 - $31.56)
Guardrail	Any	Steel Post	Feet	63,410	69,020	24	22	14%	$15.07	$27.85	$23.00	($18.50 - $34.66)
Guardrail	Any	Wood Post	Feet	15,499	12,822	9	7	14%	$22.63	$26.22	$20.60	($19.33 - $31.55)

Table A-5.7. Installation - CPI-Adjusted Initial Estimated Unit Costs (PDBS) – All items

Estimated Unit Cost (PDBS), All Items, CPI Adjustment

Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	95	6%	$12.88	$21.19	$17.79	($13.91 - $23.74)
Attenuator	Any	Any	Each	4,345	4,218	742	740	4%	$4,424.94	$6,180.65	$3,347.76	($2,851.71 - $7,841.65)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	19	7%	$21,848.89	$23,603.72	$24,701.20	($21,186.54 - $26,482.62)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	70	2%	$16,756.48	$17,419.28	$17,048.71	($15,366.37 - $18,978.24)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	46	3%	$4,775.83	$4,871.94	$4,685.22	($4,465.94 - $5,137.88)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	14	11	8	8	4%	$29,084.29	$27,848.90	$26,918.75	($26,077.81 - $29,462.54)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	101	2%	$8,382.56	$8,787.97	$8,786.49	($8,056.11 - $9,406.35)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	318	1%	$3,051.64	$3,199.68	$3,086.14	($2,846.65 - $3,375.12)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	54	5%	$3,749.75	$3,844.47	$3,390.30	($3,097.75 - $4,056.47)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	117	7%	$2,454.50	$2,771.00	$2,436.73	($2,253.73 - $2,734.25)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	5	10%	$4,293.36	$3,693.78	$3,483.04	($2,947.47 - $4,350.00)
Concrete	Any	Any	Feet	378,330	373,284	188	188	3%	$46.00	$65.25	$58.28	($50.29 - $73.20)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	21	6%	$71.99	$84.09	$82.03	($69.06 - $92.38)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	155	3%	$45.43	$61.08	$55.73	($49.40 - $65.69)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	13	11%	$94.61	$115.39	$92.38	($81.95 - $155.00)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	12%	$88.43	$92.31	$88.00	($71.98 - $93.87)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		
Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	171	3%	$46.90	$61.90	$57.00	($50.21 - $67.81)

Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	13	7%	$66.32	$79.03	$75.91	($59.86 - $87.50)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	154	3%	$45.43	$60.52	$55.66	($49.31 - $65.61)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	749	2%	$24.02	$30.08	$25.68	($20.88 - $34.47)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	329	2%	$22.55	$26.14	$23.03	($20.15 - $30.72)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	161	3%	$21.52	$25.43	$22.72	($19.98 - $28.17)

Table A-5.8. Installation - CPI-Adjusted Initial Paid Unit Costs Based on Adjusted Quantities – All Items

Paid Unit Cost, Adjusted Quantities, All Items, CPI Adjustment												
Barrier Type	**Material**	**Attribute**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Any	Any	Feet	1,429,048	1,380,955	95	83	10%	$12.74	$25.65	$18.88	($14.49 - $26.40)
Attenuator	Any	Any	Each	4,345	4,218	742	663	4%	$4,835.81	$6,914.18	$3,499.84	($2,846.7 - $7,942.6)
Attenuator	Any	A - Reusable, Wide	Each	38	35	19	16	14%	$24,690.23	$29,212.17	$24,970.63	($20,008.55 - $36,714.93)
Attenuator	Any	B - Reusable, Narrow	Each	195	183	70	64	6%	$21,169.61	$20,405.34	$18,006.82	($15,366.37 - $25,768.60)
Attenuator	Any	C - Median W-Beam End Treatment	Each	406	368	46	39	6%	$5,894.62	$5,791.68	$4,782.62	($4,540.00 - $6,140.62)
Attenuator	Any	D - Polyethylene, Low Maint/Self-Restoring	Each	14	11	8	7	4%	$27,783.07	$27,207.70	$26,635.04	($25,790.15 - $27,878.32)
Attenuator	Any	F - Concrete End Treatment	Each	301	280	101	90	4%	$9,516.21	$9,866.22	$8,939.33	($8,286.59 - $10,426.10)
Attenuator	Any	G - W-Beam Tangent End Treatment	Each	2,067	2,049	318	304	3%	$3,341.89	$3,529.11	$3,138.75	($2,834.85 - $3,762.58)
Attenuator	Any	G - W-Beam Tangent End Treatment (MASH)	Each	508	501	56	29	5%	$2,986.68	$3,253.11	$3,100.00	($2,970.83 - $3,531.00)
Attenuator	Any	H - W-Beam Flared End Treatment	Each	786	761	117	110	4%	$2,736.63	$2,964.33	$2,559.26	($2,296.92 - $3,157.61)
Attenuator	Any	H - W-Beam Flared End Treatment (MASH)	Each	26	26	5	3	12%	$4,124.70	$3,567.14	$3,483.04	($3,175.72 - $3,916.52)
Concrete	Any	Any	Feet	378,330	373,284	188	161	4%	$46.78	$72.17	$61.51	($50.67 - $84.27)
Concrete	Any	Constant Slope	Feet	27,241	26,971	21	20	9%	$72.25	$86.81	$82.96	($70.26 - $90.03)
Concrete	Any	New Jersey Shape	Feet	292,431	287,655	155	130	5%	$46.29	$69.31	$58.65	($49.96 - $77.29)
Concrete	Cast-In-Place	Any	Feet	7,940	7,940	13	12	15%	$90.02	$96.94	$87.74	($70.26 - $110.58)
Concrete	Cast-In-Place	Constant Slope	Feet	6,978	6,978	8	8	6%	$88.08	$79.60	$81.47	($70.26 - $90.03)
Concrete	Cast-In-Place	New Jersey Shape	Feet	20	20	1	1		$147.26	$147.26		

Concrete	Pre-Cast	Any	Feet	318,454	313,408	171	145	4%	$47.81	$70.85	$59.22	($50.67 - $81.52)
Concrete	Pre-Cast	Constant Slope	Feet	20,263	19,993	13	12	14%	$66.73	$91.62	$82.96	($73.53 - $88.92)
Concrete	Pre-Cast	New Jersey Shape	Feet	292,411	287,635	154	129	5%	$46.28	$68.70	$58.34	($49.89 - $76.28)
Guardrail	Any	Any	Feet	1,282,056	1,261,663	750	666	3%	$23.06	$33.12	$26.55	($20.12 - $39.24)
Guardrail	Any	Steel Post	Feet	790,702	841,526	329	310	3%	$21.88	$27.54	$23.27	($19.27 - $32.43)
Guardrail	Any	Wood Post	Feet	272,039	254,950	161	146	6%	$24.44	$31.88	$23.98	($20.05 - $34.38)

Table A-5.9. Other Project Costs - CPI-Adjusted Paid Initial Unit Costs Based on Initial Quantities (all items) for Non-Maintenance Actions

Paid Unit Cost, All Items, CPI Adjustment											
Barrier Type	**Action**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Relocate	Feet	21,033	21,033	7	7	45%	$13.65	$29.65	$11.75	($9.66 - $31.80)
Cable	Repair	Each	1	1	1	1	--	$12,097.62	$12,097.62	--	--
Cable	Salvage	Feet	45,196	45,196	4	4	23%	$9.24	$16.98	$16.51	($13.06 - $20.43)
Cable	Tension Gauge Applied	Each	18	18	16	15	9%	$2,706.10	$2,720.63	$2,534.08	($2,423.71 - $3,034.39)
Concrete	Relocate	Feet	16,637	16,637	17	14	32%	$6.54	$16.40	$10.71	($6.14 - $15.55)
Concrete	Replace	Feet	95	95	1	1	--	$17.87	$17.87	--	--
Concrete	Reset	Feet	1,718	1,718	6	4	29%	$9.72	$10.99	$10.37	($6.32 - $15.04)
Concrete	Salvage	Each	484	484	3	2	74%	$153.72	$93.70	$93.70	($59.17 - $128.23)
Attenuator	Raise	Each	2	2	2	2	34%	$1,908.94	$1,908.94	$1,908.94	($1,586.52 - $2,231.37)
Attenuator	Relocate	Each	36	36	25	22	18%	$3,627.36	$3,664.19	$2,451.07	($2,112.17 - $4,093.81)
Attenuator	Replace	Each	11	11	2	2	52%	$3,454.71	$6,045.75	$6,045.75	($4,462.34 - $7,629.16)
Attenuator	Salvage	Each	11	5	3	1	--	$1,792.74	$1,792.74	$1,792.74	($1,792.74 - $1,792.74)

Guardrail	Raise	Each	9,670	9,742	2	2	34%	$15.67	$13.87	$13.87	($11.51 - $16.24)
Guardrail	Raise	Feet	69,643	69,643	21	18	13%	$2.64	$2.81	$2.37	($1.75 - $3.28)
Guardrail	Repair	Feet	84	84	1	1	--	$20.43	$20.43	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$8.43	$8.43	--	--

Table A-5.10. Other Project Costs - CPI-Adjusted Estimated Unit Costs (PDBS) (all items) for Non-Maintenance Actions

Estimated Unit Cost (PDBS), All Items, CPI Adjustment											
Barrier Type	**Action**	**Unit of Measure**	**Quantity (Original)**	**Quantity (Adjusted)**	**Total Records**	**Records with Costs**	**Relative Standard Error**	**Weighted Average Cost**	**Average Cost**	**Median Cost**	**Interquartile Range**
Cable	Relocate	Feet	21,033	21,033	7	7	22%	$11.97	$16.86	$11.66	($9.24 - $22.76)
Cable	Repair	Each	1	1	1	1	--	$12,097.62	$12,097.62	--	--
Cable	Salvage	Feet	45,196	45,196	4	4	25%	$8.55	$14.44	$12.62	($10.63 - $16.42)
Cable	Tension Gauge Applied	Each	18	18	16	16	7%	$2,587.70	$2,576.37	$2,525.71	($2,438.60 - $2,871.02)
Concrete	Relocate	Feet	16,637	16,637	17	17	29%	$6.92	$14.01	$9.05	($6.50 - $15.89)
Concrete	Replace	Feet	95	95	1	1	--	$22.34	$22.34	--	--
Concrete	Reset	Feet	1,718	1,718	6	6	21%	$5.12	$7.19	$5.82	($4.71 - $9.39)
Concrete	Salvage	Each	484	484	3	3	41%	$193.29	$144.77	$204.83	($114.74 - $204.83)
Attenuator	Raise	Each	2	2	2	2	34%	$954.47	$954.47	$954.47	($793.26 - $1,115.68)
Attenuator	Relocate	Each	36	36	25	25	14%	$3,328.75	$3,238.88	$2,406.37	($2,092.50 - $3,661.87)
Attenuator	Replace	Each	11	11	2	2	23%	$3,035.96	$3,742.61	$3,742.61	($3,310.77 - $4,174.45)
Attenuator	Salvage	Each	11	5	3	3	62%	$372.82	$801.30	$399.02	($305.58 - $1,095.88)

Guardrail	Raise	Each	9,670	9,742	2	2	0%	$17.26	$17.26	$17.26	($17.26 - $17.26)
Guardrail	Raise	Feet	69,643	69,643	21	21	10%	$2.56	$2.91	$2.40	($2.05 - $3.37)
Guardrail	Repair	Feet	84	84	1	1	--	$20.92	$20.92	--	--
Guardrail	Replace	Feet	350	350	1	1	--	$8.43	$8.43	--	--