SUSTAINABILITY COSTING TO AID BRIDGE MANAGEMENT DECISION MAKING:

A CASE STUDY ON BRIDGE DECK EXPANSION JOINT REPLACEMENTS

by

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ABSTRACT

Many bridges in this country have reached their intended service-life, and are deemed in need of maintenance, rehabilitation, and replacement services. A life cycle inventory collects relevant information about sustainability impacts that can be used to assess the effect of decisions on the economy, environment and society. Sustainability is important because it considers impacts that are externalized from traditional costing systems; so the impacts result in costs but bridge owners do not measure or pay those costs directly. Bridge management sustainability assessment can be thought of as impacting owners, road users, and the environment. As funding for bridge maintenance, rehabilitation, and replacement services dwindle there are greater incentives for sustainable decision making. The development of inventories that assist practitioners in exercising sustainable bridge management techniques are increasingly becoming relevant in bridge management systems (BMS). The bidding process for bridge repair projects illustrates how including sustainable assessment into decision-making can improve upon BMS. Typically, A+B bidding considers both owner costs per item (A) and the costs incurred to the road users as a result of the time to complete the project (B); monetary values are assigned to the time necessary to complete the project and the bidder with the lowest total costs (A+B) is rewarded. The manner at which time is costed is dependent on the agency and can consider road user and vehicle operating costs. However, during traditions construction operations. the costs incurred to society, specifically road users, through travel delays and increased vehicle operation costs are being disregarded. In addition, the environmental costs to human health from pollutant emissions are ignored. These impacts can be greater from specific maintenance,

rehabilitation, and replacement service operations and differ from normal traffic patterns.

By incorporating the costs incurred to users and the environment, both efficient and sustainable practices can be incentivized, therefore catalyzing contractors to further develop detailed and sustainable plans when bidding for and carrying out a project. For this study, we investigated various maintenance, rehabilitation and replacement actions that are pivotal to the structural health of a bridge. As a case study, the impacts of different deck expansion joint rehabilitation/replacement options measured sustainability impacts in the units of dollars. Thus, costs are associated with impacts incurred by the owner, user, and environment and are summed to provide a total cost to score the overall efficiency and sustainability of each option. Employing the A+B+C costing method, the options with the lowest cost prove to be the most efficient and sustainable.

A full-depth replacement of an abutment expansion joint, on a particular bridge, was the primary focus of the case-study conducted. The joint's headers were fully removed as were the armoring and in-place sealant. Using the A+B+C costing method, the most sustainable joint maintenance program, for the particular abutment expansion joint, was determined for the bridge's remaining service life. It was found that the most cost effective joint maintenance program includes a full depth removal of the headers in 2015, and a partial depth replacement of the headers with Class A concrete in 2027. From these findings, the best option is an open compression seal implemented after the full depth replacement in 2015, and replacing the open compression seal with a strip seal in 2030. The lowest cost to the owner, users, and the environment for joint maintenance and replacement for the remaining life of the bridge is approximately $188,000.00. The most expensive joint maintenance program includes a full depth removal of the headers in 2015, and 7 partial depth replacement of the headers with elastomeric concrete; the headers replacement schedule would be supplemented with a new strip seal implemented in 2015 and open compressions seals implemented in 2030 and 2036. The most expensive option would cost approximately $285,000.00, approximately 52% more expensive than the optimized program. Within each program considered the owner costs ranged between 10-15% of the total costs, the societal costs ranged between 80-90% of the total costs while the environmental costs ranged between 2.6 and 2.7% of the total costs.

Chapter 1

INTRODUCTION

1.1 Scope of Research

Transportation agencies spend millions of dollars to maintain, rehabilitate, and replace bridge expansion joints each year. In fact, a survey of 34 U.S. state department agencies and 10 Canadian provincial agencies, found that a preventive bridge maintenance program specifically for joints should be established so that such components can be inspected at more frequent intervals: such an endeavor would be cost effective (Purvis, 2003). The agencies surveyed also expressed that decision making for joint implementation, maintenance and repair is done without "objective performance data." Life cycle cost analysis is needed when making decisions about joints (Purvis, 2003). With more informed decision making based on performance data, bridge owners would be able to make decisions that would result in more efficient practices - lowering the costs and impacts of joint rehabilitation and replacement to themselves as well as to the users of the structure.

The impacts of different deck expansion joint rehabilitation/replacement options were measured as costs with units of U.S. dollars. Thus, costs associated with impacts incurred to the owner, user, and environment were summed to provide an overall cost, or score, of the efficiency and sustainability of each option. Figure 1 provides a depiction of the relevant owner, user, and environment impacts considered when performing such a sustainability analysis; the depiction is known as the "Triple Bottom Line" . Lowest cost options prove to be the most efficient and sustainable.

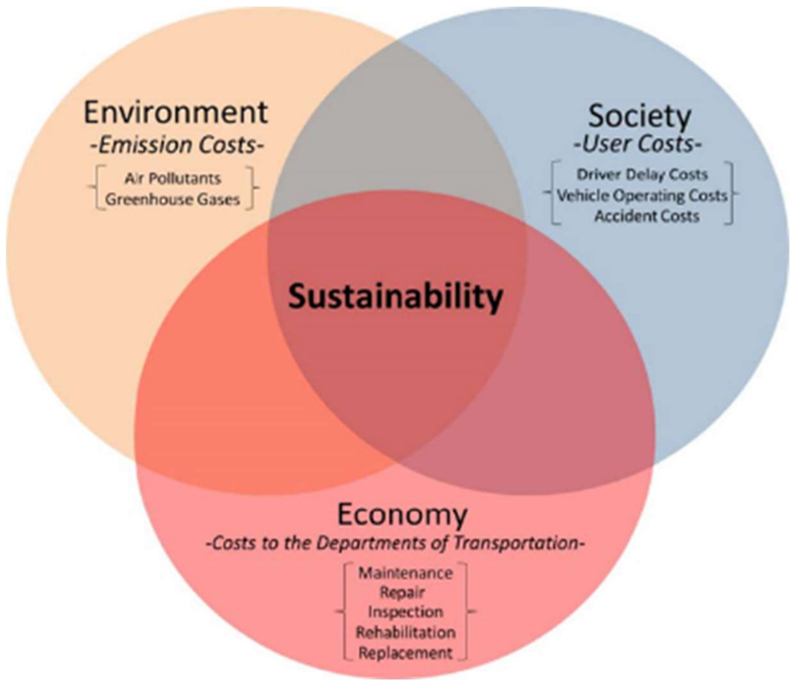


Figure 1: The LCA "Triple Bottom Line"

In determining the sustainability costs, a construction crew was shadowed while performing various deck patching, joint replacement, and joint rehabilitation tasks. Owner costs were determined by the duration, material consumption, and worker hours for each tool used in every joint rehabilitation task. Idle time of workers and tools was also considered as a cost. User costs were determined by the lost time incurred to passengers in vehicles and the increase in vehicle operating costs due to the presence of a work-zone, lane closures, and detours. The cost to the environmental was determined by the amount of criteria pollutants emissions (in weight) from tools used for joint rehabilitation and increased emissions due to the presence of a work-zone, lane closures, and detours. These emission weights were multiplied by cost factors to calculate a total environmental cost.

1.2 Terminology

The following are terms used throughout the document. If there are any terms that are ambiguous this section is to be referred to.

Abutment	The end locations of the bridge at which the superstructure rests.
Abutment Expansion Joint	The expansion joint between the abutment seat and the bridge deck.
Allocation	Proportioning resources inputted into a system as well as its expulsions dependent on various conditions.
Armoring	The metallic portion of the joint system forming an angle, one side of which is collinear with the riding surface.
Average Annual Daily Traffic (AADT)	The volume of traffic over a year divided by 365 days.
Average Daily Traffic (ADT)	The volume of traffic in one day.
Average Vehicle Occupancy (AVO)	The average number of occupants in a certain type of vehicle.
Backer Rods	A foam material, that is noodle-shaped, that fills in larger voids.
Backwall	The portion of the superstructure and deck that sits on the abutment (or bridge) seat.
Blockout	A perimeter cut into the concrete that is to be demolished.
Bridge Deck	One component of the bridge's superstructure which is the roadway of the bridge.
Bridge Superstructure	Is composed of the span, and the component of the bridge that is directly subjected to live loads.
Commercial	designates travel in a vehicle for business purposes.
Contractor	The entity responsible and reimbursed for providing certain services and labor to complete a job.
Curb	The edge of a roadway.
Dam	The area composed of the backwall and deck blockout.
Detour Delay Cost	Costs incurred to users through the usage of a roadway, specifically of a detour.

Detour Delay Time	The time lost to user through the usage of a roadway, specifically of a detour.
Detour/ Bypass	A route intended to circumvent come obstacle or closure.
Directional Split (D)	The proportion of the ADT that is split between the opposing directions on a certain structure of roadway.
Driver delay	The amount of time lost to a driver or drivers due to issues on the roadway causing delays.
Efficient Work	Work associated with no idling or loss time, all of the time put into a certain tasks yields results.
Elastomeric Concrete	A mixture of polyurethane patching material mixed with aggregate.
Fascia	The outermost edge of a particular bridge component.
Free Direction	The direction of a roadway that is not completely obstructed from vehicular volume.
Greenhouse Gases	A gas that absorbs infrared radiation.
Grout	A viscous cement based liquid that serves as an adhesive and filler.
Header	The portion of the blockout that part of the backwall, deck, or other entity.
Idle or Idling	Time spent doing nothing.
Joint	A component of the bridge that allows for differing structures to expand and shrink, while providing a smooth transition between said structure.
Life Cycle Assessment	A systematic approach in determining the environmental impacts that occur through to the development of a product or the completion of a task
Life Cycle Inventory (LCI)	A database that determines the material and energy flows as well as the environmental impact associated with a LCA.
Median	A divider between opposing directions on a roadway
Methacrylate	A bonding agent and a sealant.
Normal traffic conditions	Traffic conditions on a roadway associated with no work-zone.
Normal travel speed	The speed of traffic associated with normal traffic conditions.
Owner	The agency that has the responsibility for maintaining the bridge.
Parapet	A barrier between the roadway, the fascia, and walkways for pedestrians.
Period	A duration in time at which activities occur between the pouring of concrete during the construction phase.
Personal	Designates non-commercial travel in a vehicle.

Phase	The time spans at which the completion of a project is divided into; all stages of reconstruction occur during a phase.
Reservoir	A void created through demolition, especially the region between the joint armoring where the sealant used to exist.
Road User Cost	Referred to as the societal costs, the costs incurred to drivers and passengers through passenger delay costs and vehicle operating costs.
Silicone	Used as a gap filler during the construction phase.
Span	The distance between supports for the superstructure.
Stage	The time range at which a certain category of tasks are occurring, i.e. demolition, construction, and cleaning.
Structure	Bridge
Task	A certain action that
Through Traffic	Referring to a certain direction of traffic that is traversing the structure.
Traffic Pattern Group (TPG)	Roadways that are categorized based on their function by the Delaware Department of Transportation.
Traveler Delay Cost	Costs incurred to users through the usage of a roadway
Traveler Delay Time	Time lost to users through the usage of a roadway
Uninterrupted Flow	A constant speed at which vehicles traverse a roadway that does not include deceleration, and acceleration.
User	Those that use certain roadways and are subject to its affects.
Vehicle Operating Costs	The costs incurred to vehicle owners through upkeep and maintenance of the vehicle itself.
Vehicles	Automobiles and freight trucks.
Wage	Salary payed by the owner or contractor to its workers.
Walkway	A sidewalk or path intended for pedestrians not using vehicles to traverse a roadway or structure.
Workforce	A group of workers that are getting payed wages to provide certain services and are employed by the owner or contractor.
Work-Zone	A region of maintenance, rehabilitation, construction or reconstruction on a certain roadway.
Work-Zone Road User Cost	All road user costs incurred due to the existence of a work-zone.

Chapter 2

BACKGROUND AND LITERATURE REVIEW

2.1 Life Cycle Considerations

Bridge engineers need effective decision making tools when faced with the rehabilitation or reconstruction of bridges over the bridge life time. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) are both ways to incorporate economic concerns into repair decisions over the bridge life time. Life Cycle Assessment (LCA) considers the effects of these decisions based on environmental impacts rather than just costs as in a Life Cycle Cost Analysis (LCCA). The economic, environmental, and societal impacts are considered when sustainable life cycle analyses are being conducted. Thus, in a sustainable LCA, bridge life cycle costs are also considered while additionally providing users with further impact information beyond the scope of traditional economics.

The goals for incorporating LCA into this research are as follows:

- Develop a decision making tool intended for bridge designers and planners. The intent of such a tool is to assist planners and designers to choose the best alternative when considering what to do with a bridge that is characterized by or approaching a low serviceability level.

- Analyze and create a database of a set number of primary and unique rehabilitation and construction projects for bridges. The sensitivity of a variety of parameters within societal, economical, and environmental impact categories will be studied and assessed in order to determine the impact of such parameters for the stake-holders for whom such a study is performed.

- Quantify economical, societal, and environmental impacts of joint replacements and rehabilitation for bridge decks that will in turn help guide stake-holders and decision makers in choosing the most sustainable and profitable options when.

2.1.1 Life Cycle Assessment

ISO 14040 is the standard approach to performing a LCA (Zimoch & Rius, 2012). ISO 14040:2006 defines the following four stages to be conducted as follows and as depicted in Figure 2:

- Goal and Scope Definition
  - Includes System Boundary, Functional Unit, and Analysis Period
- Life Cycle Inventory Analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation

Reliability and uncertainty can also be considered in LCA (Harvey et al., 2010) by performing the appropriate analyses.

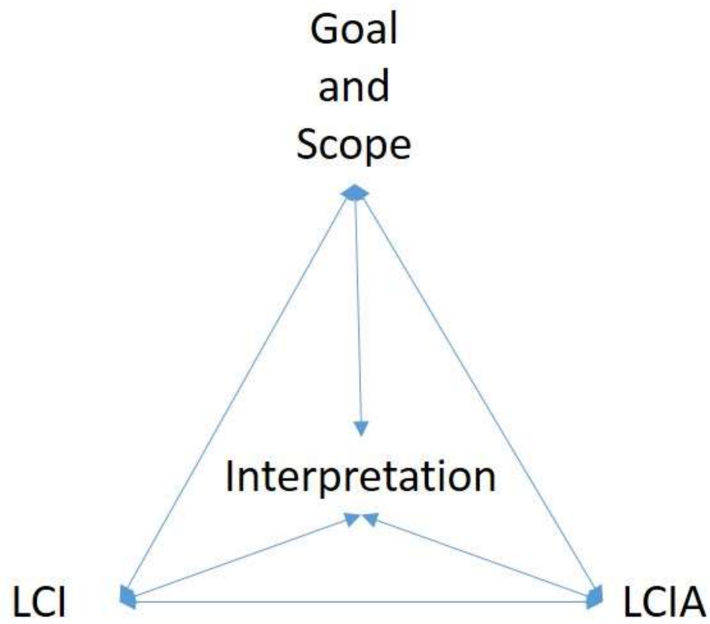


Figure 2: LCA Stages (Recreated from Zimoch, 2012)

2.1.1.1 Goal & Scope

The Goal and Scope phase of the LCA defines the subject of the analysis. The subject of the analysis can be subcategorized into the following components, and will be discussed in detail in the subsequent sections:

- System boundary
- Functional unit

2.1.1.2 System Boundary

The system boundary assesses the economic, environmental, and societal impacts for a product's life cycle stages from cradle-to-grave. Cradle-to-grave analysis looks at a product's life cycle stages from raw material extraction to material processing, manufacturing, distribution, and finally to the end-of-life (EOL) where disposal actions occur including all transportation activities. Considering a product's life cycle stages from cradle-to-gate, cradle-to-cradle, and gate-to-gate are also possible and can be defined in the Goal & Scope of an LCA (Graedel, 1998). The cradle-to-cradle method considers a secondary life at the end-of-life for the product and its elements such as from reuse, recycling, and repurposing of a product or its elements. Cradle-to-gate only analyzes the process from the extraction of raw materials to the production of the product and transport to the factory "gate" ignoring the use and disposal life cycle stages.

2.1.1.3 Functional Unit

The functional unit is key to the LCA process and must be clearly defined. The functional unit is a measure of performance that is comparable across different products (Graedel, 1998). The main performance measure for the bridge under consideration is that it is capable of supporting loads for all expected vehicular loads. Regarding bridges specifically, all applicable dimensions of the bridge and detours such as roadway length and width, number of lanes, approach length, number of columns, deck thickness, and so forth are considered in calculating and comparing the impact per each applicable and previously mentioned dimension (Harvey et al., 2010).

Bridge performance measurements can be defined as the two subcategories of functional design life and the criteria for performance (Harvey et al., 2010). The functional design life is the amount of time in years that a newly constructed bridge, or a rehabilitated bridge, would take before it is deemed no longer functional and would need rehabilitation or reconstruction. When a bridge has inadequate performance, maintenance, repair, rehabilitation, or replacement operations are needed. The criteria for performance takes into account measures that include structural capacity and level of distress, which are affected by design and construction type, permitted vehicular loads, vehicular speed, temperature, and other climatic parameters such as rain and freeze-thaw cycles. Further discussion of when a bridge does not meet the criteria for performance based on condition rating is discussed in 2.3 Bridge Management Systems section.

2.1.1.4 Analysis Period

The analysis period is the length of time of the performed study (Harvey et al., 2010) and is associated with the scope of the LCA. The analysis period, when forecasting future conditions and future maintenance and rehabilitation activities on the bridge, should consider the functional design life before and after maintenance and rehabilitation and other construction activities when applicable (Harvey et al., 2010). The age of the structure is important but not the same as the analysis period. The analysis period can be utilized to simulate and forecast future maintenance and rehabilitation, and construction activities until the end of life of the bridge. At the end of functional life of the bridge it is assumed that the bridge needs to be reconstructed.

2.1.1.5 Life Cycle Inventory

The life cycle inventory (LCI) takes into account all raw materials, energy, or waste attributable to the life cycle stage, also called phase, of a product. Table 1 lists examples of LCI items. The LCI is a database of impacts for all associated products and tasks. It is important to note that if an LCA is applied to a structure that is subject to rehabilitation, the components of the structure that is not subject to change are excluded from the LCA.

Table 1: Possible Life Cycle Inventory Items (Harvey et al., 2010)

Material flows	Energy Consumption	Greenhouse Gas Emissions	Air Pollutants	Water Pollutants (Solid waste flow)
Fossil/non-renewable resource flows	Combusted energy	CO_2	Volatile Organic Compounds (VOC)	Toxic materials
Water flows	Feedstock energy	CH_4	PM_{10}	Hazardous Waste
		N_20	$PM_{2.5}$	
			SO_2	
			CO	
			Lead	

Examples of possible life cycle stage tasks that use raw materials and energy or create waste for a bridge (production, implementation, use and end-of-life) are provided in Table 2.

Table 2: LCA Stage Considerations (Harvey et al., 2010)

Production Stage (Material Extraction and Production Stage)	Implementation Stage (Construction/Rehabilitation and Maintenance Stage)	Use Stage	End-of-Life Stage (EOL)
Raw material acquisition (Excavation and refining may be subject to cut-off)	Transportation to the site for all materials and equipment that is to be utilized in order to complete this Stage	Additional consumption of fuel due to bridge deck deterioration due to	Material can either be recycled or relinquished into a landfill
	Distance covered to transport material	Fuel economy of vehicles traveling on deteriorated deck	

	Fuel emissions of transporting vehicles	Damage to freight	
		Tire wear	
		Construction/rehabilitation traffic	
		Traffic growth	
		Traffic size and rate of traffic size change	
		Speed Distribution	
Raw material production	The manufacturing and utilization of all tools used	Fuel consumption due to varying types of maintenance	Emissions and fuel used to demolish the site must be considered
	Hour of mechanical tool usage	Construction/rehabilitation traffic	
	Associated fuel emissions of tool usage	Traffic growth	
		Traffic size and rate of traffic size change	
		Speed Distribution	
Feedstock energy of producing materials (Oil refining may be subject to cut-off)	Water transport to site	Roadway lighting	Consideration of the amount of emissions and usage of fuel and recourses in order to allocate remnants of site to either recycling locations or to landfills
	Volume of water used		
Technology and Equipment utilization in material production (This step may be subject to cut-off)	Emissions and fuel consumption by vehicles in construction	Water pollution from runoff	
	Type of traffic that is in queue		
	Speed Distribution		
	Traffic size and rate of traffic size change		
	Predicted emission standards		
Transportation of all materials at all stages in material production Stage.	Consumed energy for lighting and implementation of signs		
	Temporary Infrastructure		

2.1.1.6 Impact Assessment

The life cycle impact assessment (LCIA) utilizes the data provided in the LCI to evaluate the impacts to the owner, user, and environment from each task, life cycle stage, and to the product as a whole. In order to perform a complete LCIA, the impacts and impact categories that will be evaluated must first be established (Zimoch & Rius, 2012). After determining the impact categories, the data from the LCI are used to calculate impacts such as the amount of CO_2 and methane emissions (Harvey et al., 2010). One approach is to convert all impact categories into a single score to allow comparison of owner, user, and environmental costs, and reporting with common units such as converting the impacts of global warming to human health and ecological damage to costs (Harvey et al., 2010).

2.1.1.7 Interpretation

Interpretation, though provided as the final stage, should be implemented iteratively throughout the entire LCA process. This phase makes recommendations from the life cycle impact assessment (LCIA). The limitations, reliability, and accuracy of the data and conclusions must also be stated and considered. Through the use of statistical analyses, consideration of subjective assessments by professionals based on experience, assumptions, sensitivity analyses, and consistency checks, recommendations are made while considering applicability, accuracy, and limitations of the data and findings (Zimoch & Rius, 2012).

2.1.1.8 Sensitivity Analysis

When performing an LCA, often data for the life cycle inventory (LCI) cannot be found for the bridge location; if that is the case, the data that is most relevant must be used. To minimize discrepancies, it is useful to do a scenario and/or sensitivity analysis to see how much a change in the input data influences the outcome. Techniques such as Monte Carlo simulation can be used to measure the degree of reliability in the analysis. Traffic data contributes substantially to environmental, economic, and societal impacts; however, traffic data can be convoluted and unreliable. For traffic data, it is important to utilize scenario analyses to assess the degree of uncertainty in data. Additionally, it is important to test the robustness of the LCA model by scenario tests and sensitivity analyses with functional units determined in other studies (Harvey et al., 2010).

2.1.2 Life Cycle Cost Analysis

As the costs necessary to rehabilitate and replace aging bridges increases, effort is being directed to study and develop solutions to reduce lifecycle costs. Traditionally, a life cycle cost analysis (LCCA) of bridges determines optimal and efficient maintenance strategies for cost savings strategies throughout the expected life of the bridge (Itoh & Kitagawa, 2003). A LCCA is the sum of all direct costs and agency costs, including all necessary repair and maintenance expenditures, customarily over 100 years (Nishibayashi, Kanjo, & Katayama, 2006). LCCAs are often employed in bridge management systems (BMSs), a field of computerized decision-support modeling, intended to aid bridge owners in practicing cost effective decision making through planning and estimating the economic and structural health impacts of bridges.

LCCAs model and compare different management strategies for bridge lifetime costs. Cost modeling is dependent on data inventories that provide field and experience-based accounts. Updating data at a regular interval is needed for cost accuracy. However, collection of such data incurs high costs to the owner since the collection of such data is extensive and thus time consuming (Hearn et al., 2000). Due to the relatively recent development and implementation of LCCAs in BMSs "costing methods and data are suitable for network-level BMS models but not for project level analysis" (Hearn et al., 2000)." Due to the variety of bridge management strategies and associated practices, modeling these strategies and practices can be highly inaccurate (Itoh & Kitagawa, 2003).

A fusion of agency costs and user costs is shown in Figure 3. User costs can be analyzed separately, but not independently of agency costs. The initial (investment) costs are incurred by the owner during the design and construction phases of the project. Annual costs are those that are incurred throughout the year due to rehabilitation from expected small structural defects. Period costs are incurred after a certain number of years due to more significant structural defects that need comparatively larger construction and rehabilitation efforts and costs. The salvage value (disposal cost) at the end of the bridge's life can be positive or negative. Traffic delays due to repairs, regular inspections, and especially major repairs create user costs, thereby decreasing the benefits to the users due to bridge repair and maintenance actions.

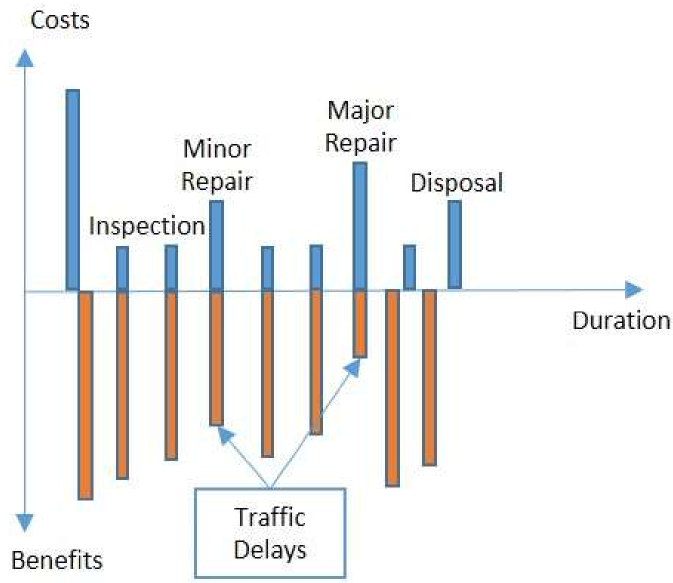


Figure 3: User and Agency Costs (Recreated from Troive, 1998)

In addition to costs to users, costs to society are incurred and considered in a combined LCA-LCCA as depicted in Figure 4; traditionally a LCCA would stem only from the agency costs.

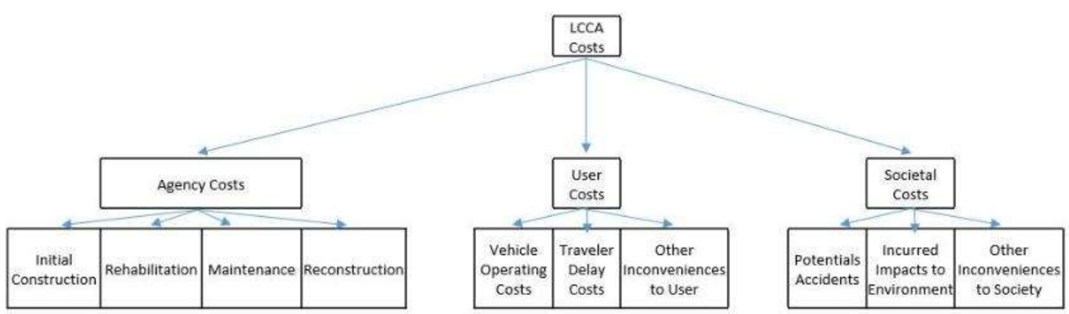


Figure 4: Combined LCA-LCCA Cost Framework (Recreated from Ozbay et al., 2003)

Kendall, Keoleian, and Helfand's created a combined LCA-LCCA model to compare bridge life time costs of two bridge deck replacement options. In this study, owner costs for construction events such as deck replacements, resurfacing, and patching were considered. Material, labor and equipment usage were collected to calculate these costs. All costs were discounted. It is important to define what is considered as owner costs, determine owner costs from actual data, and apply these costs over the lifespan of the structure (Kendall, Keoleian, & Helfand, 2008).

2.1.2.1 Net Present Value and Discount Rates

It is most common that life cycle costs are calculated using the Net Present Value (NPV) method (Jutila et al., 2007). The NPV theorem collects all costs incurred over the life of the bridge and discounts this value to the present-day value, or present value (PV) using a certain discount rate. The United States Office of Management and Budget (OMB) determines the real discount rate (Office of Management and Budget, 2005).

How to discount the environment is more difficult than using the OMB factor. The environmental impact discount rate is produced differently than the discount rate of the private market because it is assumed that society is underinvesting in the environment (Gramlich, 1990). Pollution damages can be exponentially discounted by what is defined as a sliding discount rate that accounts for the immediate, near, and medium future (Weitzman, 2001). The sliding discount rate is utilized due to the fact that there is ample uncertainty associated with environmental impacts, especially in the future, where such estimates are increasingly difficult and unknown (Weitzman, 1998).

The sliding discount rate, developed by Weitzman, was determined after a technical survey that gauged over 2,000 professional economists to provide values for the near, medium, and distant future (Weitzman, 2001). The discount rate chosen can affect the results dramatically and in ways that are controversial and not agreed upon by experts. Sensitivity analysis is thus recommended to appropriately select discounting rates (Kendall, Keoleian, and Helfand, 2008).

Discount rates, however, are associated with a degree of uncertainty; are such discount rates employed it is a concern that such uncertainties would be compounded. Discount rates are indeed controversial for reasons such as the associated uncertainty and magnitude of how their application impacts overall costs. Being that discount rates can affect the overall cost of a project by an ample amount, they will not be considered in this study.

2.2 Costs

Three types of costs are considered in this study: owner, user, and environmental costs. Owner costs are those incurred to owners through the completion of a task or project including material usages and wages. User costs consist of user delay and vehicle operating costs. Environmental costs are due to the increase of vehicular and motor driven usages resulting in greater pollutant impacts that are monetized. All three of these costs together make up a way to measure sustainability impacts through costing.

2.2.1 Agency (Owner) costs

Owner costs are defined as consisting of three components as follows:

- Acquisition costs, including but not limited to, planning and designing for construction and maintenance and rehabilitation.
- Life support cost (LSC) or all foreseen costs incurred during the lifetime of the bridge, including maintenance, repair, and rehabilitation. This is the total investment in equipment and resources necessary for M&R and all other operations to keep the structure functional.
- Future costs of negative consequences which could be considered as part of the user or societal cost parameters (Jutila et al., 2007).

Thus, the owner costs, take into consideration the costs necessary to plan, gain access, and provide the staff equipped with the necessary tools to provide maintenance actions to the structure in question. Such costs include the costs associated with acquiring and producing documentation and inspection reports, tools necessary to complete the tasks, and educating the workforce to perform said actions.

This costing method, however, does not specifically take into consideration other aspects associated with in-field operations that create overhead to owners in the same depth as the temporary material and spare parts costs associated with the LSC. Such undefined costs include wages and fuel consumption. To simulate the costs associated with such operations, information must also be provided regarding the work rates associated with the project, which ties into the wage costs, and the rate at which particular materials are used to complete certain tasks (including fuel). For the sake of simulation, the number of workers and the impact that said workers provide on the completion of the project is imperative; hence the importance of including factors that can be used to scale the costs associated with a task, such as the number of workers, wages, and fuel costs, incurred to the owner to be applied to other operations were that task to differ in deliverables, machinery, or personnel.

2.2.2 Societal Costs

One of the three pillars of sustainability is society (Figure 1). Thus the impact incurred to society must be considered. In defining what societal costs for joint replacement operations and BMS in general various costing considerations will be discussed. Ultimately in this research passenger delay and increased vehicle operating costs are considered as societal costs.

The "Work Zone Road User Costs-Concepts and Applications" (WZRUC) document, produced by the Federal Highway Administration (FHWA), and distributed under the backing of the U.S. Department of Transportation, serves as a guideline that monetizes the adverse effects associated with work-zones so that decision makers are informed of the holistic impacts (converted into monetary units) that result from their decisions. The 2003 "Manual on Uniform Traffic Control Devices for Streets and Highway" (MUTCD) refers to a work-zone as a segment of highway that is subjected to construction, rehabilitative, maintenance, and utility work (United States Department of Transportation, 2003). Such delay costs are found for automobiles, single unit trucks, and combination trucks based on estimates developed by the Federal Highway Administration (FHWA) (Walls III & Smith, 1998). The work-zone affects the common person through potential traveler delay and vehicle operating costs, accidents, noise impacts, and impacts on the environment (Mallela & Sadavisam, 2011) are listed in Figure 5.

Figure 5: Work-zone User Costs (Mallela & Sadavisam, 2011)

The emission costs will not be considered as a societal impact contributor, but will be referred to independently in the environmental impact sections as one of the three pillars of sustainability (Figure 1). Similarly, impacts to nearby projects will not be considered in this study. Thus, the main costs taken into consideration regarding the societal costs are the road user costs such as: driver delay, vehicle operation, and accident costs, and are presented in detail in the following sections.

2.2.2.1 Driver Delay Costs

Costs can be incurred by users due to risks from a work-zone for bridge maintenance and rehabilitation procedures. These risks include reduced speeds, detours, and increased number of accidents, and can be categorized as predicted costs created by expenses due to driver delays, vehicle operations, and accidents. Three methods of costing driver delay are discussed: BridgeLCC, ETSI Project (Stage 1), and a method created by the FHWA (Mallela & Sadavisam, 2011). BridgeLCC is a life cycle costing software developed by the National Institute of Standards and Technology (NIST) (Ehlen & Rushing, 2003). The European Telecommunications Standards Institute (or ETSI) Project (Stage 1) is a joint study between representatives in Finland, Norway and Sweden, distributed from the Helsinki University of Technology Laboratory of Bridge Engineering, that intends to provide engineers with the resources with the intent of optimizing bridges especially within the categories of "technique, economics, aesthetics, repair etc…" (Jutila et al., 2007).

The driver delay costs provided by the BridgeLCC software, does not take into consideration a variety of factors such as:

- How delay times change based on the completion of tasks and stages of the operation and thus work-zone and lane closure change throughout the project,
- The number of passengers in a vehicle,
- The types of vehicles,
- The variation of the weighted average cost incurred to drivers per hour of time,
- The detours, and
- The total number of vehicles and number of vehicle types that traverse the detours.

For accurately simulating costs, the effect of detours, vehicle types, occupancy of said vehicle types, and consideration regarding the work-zone set-up is imperative.

The methods presented by ETSI Stage 1 in determining the driver delay costs, however, do expand upon the factors presented by the BridgeLCC software, by taking into account the variations in valuing time based on the type of transportation particular vehicles are providing, by considering the number of commercial vehicles and their associated costing factors as well. The method provided by ETSI also acknowledges the effect of other roadways that may be affected by the work-zone.

The ETSI approach, though providing a further detailed method than the initial equation provided, also requires traveler information and costing data that may not be available in all locations. For example, the Delaware Department of Transportation (DelDOT) provides driver delay costing factors for automobiles, light trucks and heavy trucks ("Design Guidance Memorandum Road User Cost Analysis," 2015) but does not separate the data into commercial and non-commercial vehicles nor considers impacts to passengers inside the vehicles.

The ETSI approach neglects a variety of factors;

- Traffic speed during roadwork,
- Traffic speed during normal conditions, and
- How the number of commercial vehicles varies before and over the duration of the project.

Such variations impact the overall driver delay time and cost. Thus, the method provided by ETSI also does not consider the manner at which speed varies during normal operations and during the work-zone on the structure and on detours at a specific time of day. The approach does consider the average daily traffic (ADT) at a specific time of day though it neglects the number of passengers within each vehicle type. The FHWA's "Work Zone Road User Costs-Concepts and Applications" document, provides guidance, techniques, and resources in the pursuit of determining passenger delay time by considering vehicle-types, commercial or non-commercial travel, vehicle occupancy, travel delay time on the structure, detour delay time, and costs as shown in Figure 6 (Mallela & Sadavisam, 2011).

The FHWA method first emphasizes the necessity of determining the delay time that is associated with a particular work-zone as depicted in Figure 6. To determine the delay time, the speed change, reduced speed, stopping, queue, and detour delays must be determined. The speed change is defined as the time lost to decelerating upon approaching the work-zone then accelerating after traversing the work-zone. The reduced speed delay is defined as the delay experienced by vehicles upon traveling at speeds slower than those that are posted on that particular roadway. The stopping delay is defined as the time lost to vehicles that come to a complete stop within the vicinity of the work-zone. The queue delay is associated with heavy traffic and is the time lost to vehicles that slowly traverses the roadway during the presence of a queue. The delay associated with vehicles that either chose or are forced to traverse detours is referred to as the detour delay (Mallela & Sadavisam, 2011). Not all agencies consider the speed change and stopping delays when considering and providing delay time calculations (Mallela & Sadavisam, 2011).

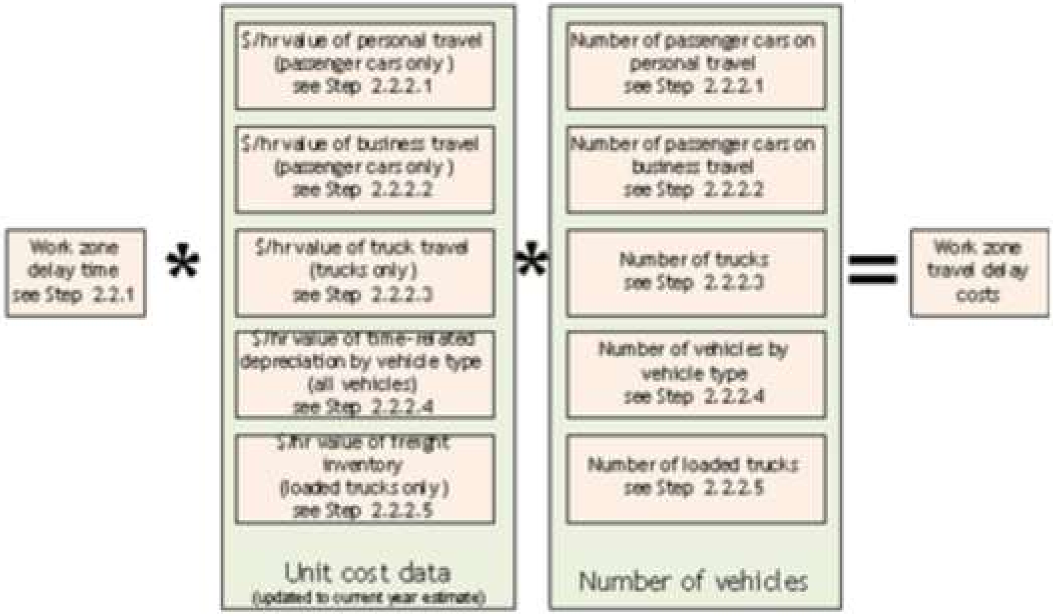


Figure 6: Necessary constituents in determining total work zone travel delay costs (Mallela & Sadavisam, 2011)

In determining the traveler delay costs, the monetized value of time must be determined. Specifically, the monetized value of time for passengers and motorists in automobiles traveling for both personal and business reasons must be accounted for as must passengers and motorists traveling in both freight and truck vehicles. The total monetary value of travel time is the sum of the lost delay time incurred to motorists and passengers mentioned previously as well as the costs incurred to freight vehicles when the inventory that is carried is delayed (Mallela & Sadavisam, 2011).

The value of time of a driver is affected by the driver's location. The locations are specifically referred to as "local or intercity" (United States Department of Transportation, 2003). Per the guidelines provided by the United State Department of

Transportation Office of the Assistant Secretary for Research and Technology (OTS), by utilizing the U.S. Census Bureau's median household income (or of a particular region) by 2,080 hours and multiplying the quotient by 0.5 and 0.7, the personal hourly value of time (per person) in local and intercity locations can be determined. By multiplying the aforesaid quotient by 1, for intercity and local locations, the business hourly value of time can be determined (Belenky, 2011). Thus, after determining the number of vehicles affected by the work-zone, the travel delay incurred to each vehicle type (within each work-zone traffic delay scenario explained at the beginning of this section), the number of passengers within each vehicle, the purpose of travel for the motorist and passengers, and the median income, the total travel delay cost can be determined. Freight vehicle delay costs are further detailed by the FHWA in (Mallela & Sadavisam, 2011).

In order to calculate driver delay costs, the proportion of motorists and passengers traveling for business and personal reasons must be determined first. Table 3 shows some of the values for this ratio as reported in two separate studies.

Table 3: Ratio of motorists and passengers traveling for business and personal reasons

Study	Personal	Business	Reference
1990 NPTS	98.50%	4.20%	(Hu & Young, 1993)
2001 NHTS	91.90%	8.10%	(Hu & Reuscher, 2004)

The total amount of delays experienced by vehicles can be scaled to represent the total travel delay time experienced by the number of passengers in said vehicles. One source for determining the average vehicle occupancy (AVO) is the National Household Transportation Summary (NHTS) (Santos, McGuckin, Nakamoto, Gray, &

Liss, 2011). The travel delay time and detour delay time measure the amount of extra time incurred to drivers and passengers due to the presence of a work-zone. Thus the number of passengers and drivers must be determined to scale the lost time incurred to those that are affected by the construction process by considering the average vehicle occupancy (AVO). The AVO must be determined for motorists and passengers in automobiles and freight vehicles. The NHTS found an AVO of 1.67 for all travel purposes that had a confidence interval of 0.03 for passenger vehicles (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). Only after the representative travel and detour delay times are determined for automobiles and freight vehicles, the travel delay costs and detour delay costs can be determined.

2.2.2.2 Vehicle Operating Costs

Vehicle operating costs vary depending on the vehicle-type, distance covered, and speeds produced by the vehicle-type while driving said distances, all of which are factors that vary throughout the day with and without the presence of a work-zone. Vehicle operating costs can be defined as the "the expenses incurred by road users as a result of vehicle use (Mallela & Sadavisam, 2011)." Vehicle operating costs include the costs incurred to road users through fuel consumption, engine oil consumption, tire wear, repair and maintenance, and mileage-related depreciation. With information regarding the traffic and volume characteristics of a roadway, and its associated detours, with and without roadwork, as well as the associated vehicle operating costs per vehicle-type, the total vehicle operating costs can be determined. The first task in determining the vehicle operating cost is to determine the increased operating costs of vehicles traversing the structure and detours due to the work-zone. The total passenger vehicular operating costs traversing the structure can be found by multiplying the passenger vehicle operating costing factors by the detour length, then by the passenger vehicle ADT; on the detours, along the bypass detour can be found, by multiplying the passenger vehicle operating cost by the detour length, then by the passenger vehicle ADT on the detours. Vehicle operating costs of other vehicle types, such as freight trucks, can be determined in the same fashion as the passenger vehicles, except the ADT of that vehicle type (freight trucks) must be used as must the correct vehicle operating costing factors (for freight trucks) (Mallela & Sadavisam, 2011). By summing all vehicle operating costs (of all vehicle types) for those traversing the structure and those on the detour, the total vehicle operating costs are determined. The approach in calculating the vehicle operating costs vary between BridgeLCC (Ehlen & Rushing, 2003), ETSI (Jutila et al., 2007), and the FHWA (Mallela & Sadavisam, 2011).

The vehicle operating costs provided by the BridgeLCC considers the total duration of the project. However, throughout the duration of a project, lane closures, and the dimensions of a work-zone may very well vary based on the completion of tasks and stages of the operation. BridgeLCC does not consider the following:

- How delay times accumulate throughout the duration of the project due to changes in the work-zone;
- How all of the factors listed above vary throughout the duration of the project,
- The vehicle types on the roadway,
- Other affected roadways besides the work-zone such as detours, and
- The number of passengers in each vehicle-type.

Furthermore, different vehicle types will have different costs per mile; an average per vehicle cost factor misses these differences. With a work-zone present, vehicles travel with different speeds and for different distances on a detour, which will in turn effect the wear and tear on the vehicle and fuel consumption thus affecting the total vehicle operating costs. The BridgeLCC approach only considers the total duration lost to a single roadway and an all-encompassing costing factor for all vehicles. The affected roadways, vehicle types and their speeds, and distances traveled by each vehicle-type influence the total vehicle operating costs.

The ETSI Stage 1 approach expands upon the factors of the formula above by taking into account variations in valuing operating costs based on the type of transportation and by considering the number of commercial vehicles and their associated costing factors. The operating cost provided by ETSI distinguishes between costs for personal and commercial vehicles in terms of vehicle operation but also the costs incurred to commercial vehicles for delays in transporting goods. The ETSI approach for monetizing vehicle operating costs also requires traveler information and costing data that may not necessarily be available or applicable in all locations. The ETSI Stage 1 method also does not consider:

- The traffic speed during roadwork, the traffic speed during normal conditions, and the number of commercial traffic does not consider the manner at which such entities vary before the beginning throughout the duration of the project, and
- The manner at which speed varies before and during the work-zone on the structure and detours.

ETSI does consider how ADT varies with time.

The FHWA approach determines vehicle operating costs by considering the additional incurred costs, dependent on acceleration, deceleration, speed and distance, due to a work-zone such as fuel, engine oil, tire wear, repair and maintenance, mileage-related depreciation, and their associated costing factors as shown in Figure 7. The FHWA provides resources that clearly depict vehicle operating costing factors that are dependent on not only vehicle types, but the speed and distance covered by each vehicle-type (Mallela & Sadavisam, 2011).

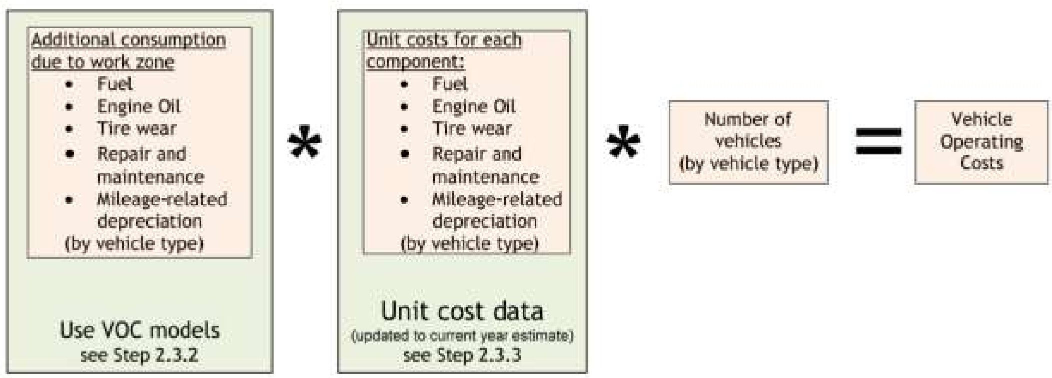


Figure 7: Vehicle Operating Cost Components (Mallela & Sadavisam, 2011)

How much vehicle operating costs increase due to a work-zone is primarily due to accelerating, decelerating, and increased distance traveled. This is considered as "Additional consumption due to work zone" (left box in Figure 7). Specifically, the total vehicle operating costs are the sum of the vehicle operating costs incurred to the vehicle (and therefore the user) through speed changes, stopping, queuing, and driving the detour (Mallela & Sadavisam, 2011).

The American Automobile Association (AAA) annual publication, "Your Driving Costs, How Much are You Really Paying to Drive", published in 2010 has estimated the following vehicle operating costs for passenger vehicles in cents/vehicle operating mile. Estimates have been found for small, medium, and large sedans, four-wheel drive sport utility vehicles, and minivans. The cost is measured in cents per vehicle operating mile for fuel, maintenance and oil, and tires. It is assumed that a vehicle drives 15,000 miles/year as can be seen in Table 4 (Mallela & Sadavisam, 2011; "Your Driving Costs," 2010).

Table 4: Driving costs in cents per mile by vehicle type (Mallela & Sadavisam, 2011; "Your Driving Costs," 2010).

Cost Component	Small Sedan	Medium Sedan	Large Sedan	4WD Sport Utility Vehicle	Minivan
Fuel	9.24	11.97	12.88	16.38	13.7
Maintenance and oil	4.21	4.42	5	4.95	4.86
Tires	0.65	0.91	0.94	0.98	0.75
Depreciation @ 15000 miles/year	15.89	23.01	32.19	33.35	26.63

Along with the estimates by AAA for the passenger vehicle operating costs, estimates regarding the vehicle operating costs of trucks were also found. In 2008, the American Transportation Research Institute (ATRI) published estimates regarding the vehicle operating costs for trucks. These estimates were based off of a gallon of diesel costing $4.69 (Trego & Murray, 2010). The values presented were of the units of cents/operating vehicle operating mile as can be seen in Table 5.

Table 5: Truck Vehicle Operating Costs ($) (Trego & Murray, 2010) Taken from (Mallela & Sadavisam, 2011

Cost Component	Trucks
Diesel Fuel (@ $4.69/gallon) No surcharge	63.4
Diesel Fuel (@ $4.69/gallon) With surcharge	21.9
Fuel taxes	6.2
Maintenance	9.2
Tires	3
Depreciation	N.A.

It should be noted that the ATRI estimates do not include depreciation values. The average vehicle operating costs of 2005 that includes depreciation factors was provided by the FHWA as can be seen in Table 6 (Mallela & Sadavisam, 2011).

Table 6: FHWA RUC Vehicle Operating Costs ($) (Copied from Mallela & Sadavisam, 2011)

Cost Component	Small Autos	Medium-sized Autos	Large Autos	SUVs	Vans	Trucks
Fuel and Oil	5.4	6.44	7.5	8.34	7.5	21.41
Maintenance and Repair	3.5	4.12	4.33	4.33	4.12	11.09
Tires	0.5	1.58	1.9	1.58	1.69	3.7
Depreciation	13.9	12.5	12.5	12	12	10.6
Total	20.59	20.59	22.17	22.7	21.75	44.64

It should be noted that more specific data for the vehicle operating costs can be found if the traffic speed during normal operations and work-zones for the bridge and detour are known. AAA, ATRI, and FHWA have vehicle operating cost estimates based on speeds. Speed information can produce more accurate values for vehicle operating costs on the structure and detours for trucks and automobiles during normal traffic on the bridge structure and when work zones are present. Equations related to the user delay and vehicle operating costs have been provided in Appendix E.1 and E.2, respectively, with supplementary commentary.

2.2.2.3 Accident costs

Accident costs are not considered in this study; however, some sources do include accident costing into their societal costs and emphasize its relevance. The reason these costs are not considered is because they are high and are associated with low accuracy. For example, "The Economic and Societal Impact of Motors Vehicle Crashed, 2010 (Revised)" of May, 2015 states that the monetarily estimated lost quality of life, the severity of crashes stored in databases, and police reporting on medical injuries can lack accuracy an issue that the study itself was tasked with, amongst other things, improving upon (Blincoe, Miller, Zaloshnja, & Lawrence, 2015). According to Section 2 of the "New Jersey Department of Transportation Road User Cost Manual", though, the department considers factors such as crash costs as a financial cost, there is still limited information regarding crash rates in work-zones due to a lack of available data and it thus does not suggest that crash costs be implemented into a road user cost study ("NJDOT Road User Cost Manual," 2015). Although such costs are not considered, a review of different practices to estimate accident costs are still provided in Appendix C.

2.2.3 Environmental Costing

There is no general consensus regarding how to monetize environmental impacts due to emitted pollutants (Mallela & Sadavisam, 2011). Kendall, Keoleian, and

Helfand's LCA model (2008) defined environmental costs as those produced by pollution damages. There are seven criteria pollutants specified by the EPA and three greenhouse gasses (CO_2, CH_4, and N_20). Six of the seven criteria pollutants and the three GHGs were considered in this study. The costs resulting from climate change such as economic impacts of sea level rise and the increased potential of human health impacts such as the increase in exposure to tropical diseases were monetized. The cost per metric ton of the carbon component of the aforementioned chemicals were found by multiplying those values by the ratio of carbon over its molecular weight.

The FHWA WZ RUC provides guidance and tools with regards to determining the magnitude of emission per pollutant-type and the associated costs of each type of pollutant based on vehicle types and the manner at which such vehicles are used (Mallela & Sadavisam, 2011). Though guidance was not provided with regards to other pollutant sources, such as on-field generators and machinery used during a project, such values would have to be found elsewhere and scaled with the costing factors.

There are two types of models that can be used to determine emission factors from vehicles: the static and the dynamic model (Mallela & Sadavisam, 2011). Static emission factor models provide emission factors as a function of vehicle speed for automobiles and trucks as shown in Table 7. Static models for determining emission factors are appropriately utilized for estimating the volume of various emitted pollutants "for long-scale planning studies where the estimations based on average speed are highly accurate; however, these models are not sensitive enough to capture the actual driving conditions such as acceleration, deceleration, idling, and cruising cycles in a work zone" (Mallela & Sadavisam, 2011), factors that were also not considered when determining the road user delay costs. Dynamic emission factor models necessitate precise traffic collection data at the exact location of the work zone in order to correctly capture the acceleration, deceleration, idling, and cruising cycles due to the work zone and traffic signals. Thus, a static model was utilized for determining the environmental impact of vehicles on the structure, traversing the work zone and for those on the detour.

The static emission factor model used is Mobile 6.2 (now called EPA MOVES) which is used by most states, though not California (Mallela & Sadavisam, 2011). The Emission Factor (EMFAC) model was developed by the California Environmental Protection Air Resource Board (CARB) and is used as a mobile vehicle emission estimation tool (California Environmental Protection Agency, Air Resource Board, 2016). An example of the FHWA Static Emission Model is provided in Table 7.

Table 7: FHWA WZ RUC Static Emissions Model Example (Recreated from Mallela & Sadavisam, 2011).

Speed	Auto (g/mi)					Trucks (g/mi)				
	CO	NO R X	PM R 10	SO R X	VOC	CO	NO R X	PM R 10	SO R X	VOC
5	16.97	1.39	0.1	0.01	1.97	31.44	16.57	0.71	0.12	3.6
10	14.25	1.21	0.07	0.01	1.48	26.81	15.19	0.63	0.12	3.18
15	12.23	1.07	0.06	0.01	1.18	20.51	13.11	0.51	0.11	2.58
20	10.79	0.97	0.05	0.01	0.99	16.68	11.7	0.42	0.11	2.19
25	9.75	0.9	0.04	0.01	0.88	14.29	10.8	0.36	0.11	1.93
30	8.98	0.86	0.04	0	0.8	12.78	10.28	0.31	0.11	1.74
35	8.42	0.83	0.04	0	0.75	11.83	10.08	0.28	0.11	1.62
40	8.02	0.81	0.03	0	0.72	11.27	10.18	0.25	0.11	1.53
45	7.77	0.81	0.03	0	0.71	11	10.59	0.23	0.11	1.47
50	7.66	0.82	0.03	0	0.7	10.98	11.35	0.22	0.11	1.42
55	7.71	0.84	0.03	0	0.71	11.19	12.54	0.21	0.11	1.4
60	7.97	0.88	0.03	0	0.73	11.69	14.3	0.2	0.11	1.38
65	8.51	0.94	0.03	0	0.76	12.55	16.87	0.2	0.11	1.38

To determine the volume of each pollutant emitted by the vehicles, the average hourly traffic (AHT) of both trucks and automobiles traversing the work zone, and on the detours, for each phase, must be considered. By multiplying the AHT determined for the road user costs, and by considering the speeds and distances associated with traversing the work zone and the detours of each phase, with the emission constants provided, the total volume of each emitted pollutant can be determined.

The WZ RUC provides a variety of sources for monetizing the emitted pollutants. Resources that monetize the environmental impacts of emissions attempt to determine the health impacts incurred to the populace due to emissions; the health impacts are monetized by estimating future expenditures of the populace in dealing with said health impacts (Mallela & Sadavisam, 2011). Thus, in urban areas where the population is denser, the costs associated with pollution would be higher than similar emission volumes were they expelled in a less densely populated suburban area. Two resources suggested by the FHWA's WZ RUC document are: the Highway Requirements System-State Version (HERS-ST) 2005 Technical Report and estimates by the California Department of Transportation (Caltrans) (Mallela & Sadavisam, 2011).

2.3 Bridge Management Systems

Bridge Management Systems (BMS) provide organized and informed decision making frameworks for many DOTs using the FHWA's established practices and guidelines. Such frameworks are intended to be referenced and implemented throughout the design and construction of newer bridges as well as maintenance, rehabilitation, and reconstruction of bridges that have already been erected. By providing an informed and expansive network regarding bridge elements as well as guidelines to maintain, rehabilitate, or replace such elements, an efficient and cost effective decisions can be made and executed benefitting owners, users, and the environment. Due to the availability of BMS to bridge owners and decision makers, structural upkeep for bridges have, in recent years, emphasized proactive strategies as opposed to those that are reactive for the sake of short-term cost effectiveness (Hearn et al., 2000). Thus, preventive actions such as maintenance has been increasingly gaining recognition as a pivotal component of BMSs.

Bridge maintenance can differ from state to state depending on the DOT's policy, budget, database, and list of actions (Hearn et al., 2000). Maintenance can generally be defined as actions that have a short duration time until completion and are considered "small," such as cleaning, or even replacing parts, or structural modifications (Hearn et al., 2000). Generally, projects that are considered large are deemed to be construction. Construction consists of replacement or major rehabilitation of structures.

2.3.1 General Condition Ratings

The General Condition Rating (GCR) is a rating system that determines the bridge conditions. The GCR rates the deck, superstructure, substructure, and culvert components of the bridge separately (Ahmad, 2011). A GCR of 4 or less for the deck or superstructure dictates that specific component of the bridge to be structurally deficient (SD). Condition ratings of 3 or less for the deck or superstructure dictates that specific component of the bridge to be functionally obsolete. If a structure has a structural deficiency or is deemed functionally obsolete (FO), the structure is considered deficient (Ahmad, 2011). Table 8 was recreated from the FHWA Bridge Preservation Guide (2011), providing a general framework of the National Bridge Inventory (NBI) GCR.

Table 8: NBI GCR Guidelines (Recreated from Ahmad, 2011)

Condition Rating	Description of Condition	Actions Required
N	Not Applicable	
9	Excellent	Preventive Maintenance
8	Very Good- no issues determined	
7	Good - minor issues found	
6	Satisfactory - minimal signs of deterioration	Preventive Maintenance and/or Repairs
5	Fair - minimal section loss and deterioration found on main structural elements	
4	Poor - increased section loss and deterioration	Rehabilitation and/or Replacement
3	Serious - further advancement of deterioration where fatigue and shear cracks may be present in steel members and concrete, respectively.	
2	Critical - Supports from the substructure may no longer be sufficient. Deterioration, section loss, and fatigue and shear cracks in various members may be more prominent. The structure should be closely monitored or closed.	
1	"Imminent" Failure- Deterioration and section loss is surmountable. The bridge is to be closed and only reopened when corrective actions taken. The bridge is no longer stable	
0	Failed Completely failed	

According to the FHWA, general condition ratings are used to evaluate the current condition of a structure against the initial condition at the time of construction. An evaluation is required of the physical condition of the following components of the bridge as indicated by the FHWA "Bridge Preservation Guide: Maintaining a Stage of Good Repair Using Cost Effective Investment Strategies" (Ahmad, 2011)

- Deck - Determining the condition of the concrete, steel or timber with regards to signs of physical deterioration such as cracking, scaling, broken welds, or splitting.
- Superstructure - Determining the condition of the superstructure with regards to signs of physical deterioration such as cracking, corrosion, section-loss, and misaligned bearings.
- Substructure - Determining the condition of the substructure with regards to signs of physical deterioration such as scour, corrosion, cracking, signs of collision damage, and any signs of misalignment.

The general condition rating (GCR) of a structure is often utilized in determining whether maintenance, rehabilitation, or reconstruction/replacement are to take place. The decision of whether to rehabilitate or repair can be determined in part by the GCR.

DOTs define what actions can be considered as maintenance, rehabilitative and reconstructive due to a number of factors. Thus, the manner at which GCRs are utilized in determining what actions are to take place, whether it be maintenance, rehabilitation, and/or construction/reconstruction depends on the state. The Virginia DOT provides a detailed and comprehensive guide regarding how it defines certain actions as well as relating GCR's to such actions ("VDOT Maintenance and Repair Manual," 2014).

VDOT expresses that bridges with one or more component with a GCR:

- less than or equal to 4 be subjected to rehabilitation and replacement,

- equal to 5 be subjected to restorative maintenance, and
- 6 or greater be subjected to preventive maintenance ("VDOT Maintenance and Repair Manual," 2014)

The Highway Bridge Program (HBP), formerly the Highway Bridge Replacement and Rehabilitation Program (HBRRP) is a type of federal funding concerned with rehabilitation and maintenance. Specifically, the HBP is for "preventive maintenance, rehabilitation or total replacement of SD or FO bridges on any public road" ("VDOT Maintenance and Repair Manual," 2014). HBP funds are available only after 10 years has passed since the last HBP funded major preventive maintenance or rehabilitation project. Funding not derived from the 10 year rule will be referred to as traditional funding. Aside from the 10-year rule, the VDOT has suggested the following itemization of funding:

- Preventive Maintenance – 15%,
- Painting – 10%,
- Restorative Maintenance – 25%, and
- Rehabilitation/Small Structure Replacement – 50% ("VDOT Maintenance and Repair Manual," 2014).

2.3.1.1 Maintenance

Maintenance activities can be characterized as routine, cyclical preventative, condition based preventative, or restorative. Preventive maintenance actions consist of a large portion of the BMS decision making provided by agencies. Preventative maintenance is applied to the bridge or bridge components that still have significant remaining life (Ahmad, 2011).

Routine maintenance is uncomplicated and can usually be carried out by standard instructions. According to FHWA's Bridge Preservation Guide, routine maintenance actions include (Ahmad, 2011):

- Bridge washing or cleaning,
- Sealing deck joints,
- Facilitating drainage,
- Sealing concrete,
- Painting steel,
- Removing channel debris,
- Protecting against scour, and
- Lubricating bearings.

Cyclical preventive maintenance does not always improve the condition of bridge elements, but it does delay future deterioration (Ahmad, 2011). Cyclical PM activities and the frequency at which they are applied can be seen in Table 9, based on the FHWA's knowledge of DOT practices (Ahmad, 2011).

Table 9: Cyclical PM Actions with Frequencies (in Years) of Application Based on FHWA Knowledge of DOT Practices (Recreated from Ahmad, 2011)

Cyclical PM Activity Examples	Commonly Used Frequencies (Years)
Wash/clean bridge decks or entire bridge	1 to 2
Install deck overlay on concrete decks such as:	
Thin bonded polymer system overlays	10 to 15
Asphalt overlays with waterproof membrane	10 to 15
Rigid overlays such as silica fume and latex modified	20 to 25
Seal concrete decks with waterproofing penetrating sealant	3 to 5
Zone coat steel beam/girder ends	10 to 15
Lubricate bearing devices	2 to 4

Condition-based preventive maintenance, or singular maintenance, are reactionary endeavors that are performed on structures that are deemed to be in good conditions (Ahmad, 2011). Locations and components of the structure that are deemed to necessitate condition-based preventive maintenance are done so post inspection, examples of condition-based preventive maintenance actions are listed below (Ahmad, 2011):

- Sealing of leaking joints
- Replacement of leaking joints
- Installation of deck overlays
- Installation of cathodic protection systems
- Complete, spot, or zone painting/coating of steel structural elements

Activities such as eliminating, sealing, or replacing leaking joints minimizes deterioration of deck reinforcement, superstructure, and substructure elements. Likewise, deck overlays aggressively retard the effects of aging and weathering of the deck, therefore increasing the life of the deck (Taavoni & Tice, 2012).

Table 10 provides a planned preventative maintenance schedule and framework has been established by the VDOT.

Table 10: Preventive Maintenance Activities According to the VDOT (Recreated from "VDOT Maintenance and Repair Manual," 2014)

Preventive, Cyclical Maintenance Activities	Preferred Cycle (yrs)	Activity Description
Bridge Deck Washing (Concrete)	1	Includes the removal and disposal of debris and pressure washing of the bridge roadway surface, joints, sidewalks, curbs, parapet walls, drainage grates, downspouts, and scuppers.
Bridge Deck Sweeping	1	Includes the removal and disposal of debris and sweeping of the bridge roadway surface, shoulders, joints, sidewalks, and curb lines.
Seats & Beam Ends Washing	2	Includes the removal and disposal of debris and pressure washing of the bridge seat, bearing areas, and 5 feet of beam-ends. Use 3 feet avg. seat width for estimation purposes.
Cutting & Removing Vegetation	2	Includes cutting, removing and disposing of vegetation, brush and trees that are on, adjacent to, or under bridges.
Routine Maintenance of Timber Structures	2	Includes tightening and/or replacing fasteners such as those used on timber decks, railing systems, and other miscellaneous connections, sealing end sections of timber elements, such as deck boards, bent caps, railings, posts, etc.
Scheduled Replacement of Compression Seal Joints	10	Includes removal of existing joint material, surface preparation and installing new joint material.
Scheduled Replacement of Pourable Joints	6	Includes removal of existing joint material, surface preparation and installing new joint material.
Cleaning and Lubricating Bearing Devices	4	Includes removal and disposal of debris, and lubricating moveable bearings.
Scheduled Installation of Thin Epoxy Concrete Overlay	15	Includes installing of new system and/or replacing existing overlay system.
Beam Ends Painting	10	Includes preparing and over-coating the end 5 feet of painted steel beams or girders that are located under open joints, except for bridges with timber decks. Replace paint system at year 30.
Removing Debris from Culverts	5	Includes the removal and disposal of debris that is collected inside and/or at inlets or outlets of culverts.

Restorative maintenance differs from routine maintenance in that it is utilized purely from a reactive perspective due to an unforeseen event (Ahmad, 2011). Table 11 provides examples of activities that the VDOT considers as restorative maintenance.

Table 11: Restorative Maintenance Activities According to the VDOT ("VDOT Maintenance and Repair Manual," 2014)

Restorative Maintenance Activities	Activity Description	Asset
Rigid Overlay	Application of latex/silica fume overlay to bridge decks	Deck
Rail repair	Repairing or maintaining the railing system on a bridge. This includes rails, parapets, curbs, safety walks and all associated supports and connections.	Deck
Asphalt Overlay	Application of asphalt overlay to bridge decks.	Deck
Concrete Superstructure Repair	Repairs to the exposed surfaces of bridge superstructures	Superstructure
Steel Superstructure Repair	Repairs to steel bridge superstructure and all related supporting activities, such as blocking and jacking of the superstructure	Superstructure
Bearing Repair	Repair, realignment or replacement of bridge bearing device	Superstructure
Paint-Superstructure	Painting or coating structural steel on a bridge	Superstructure
Paint-Superstructure	Spot painting	Superstructure
Substructure Surface Repair	Repairs to the exposed surfaces of bridge substructures	Substructure
Substructure-Repair Undermining	Filling scour holes, installing rip-rap or other scour countermeasures to prevent or stabilize scour at bridge substructure	Substructure
Approach Slab Repair	Maintenance of bridge approach slabs. Examples: repairing settlement, repairing cracks, patching, installing/repairing pressure relief joints, replacing overlay.	Bridge
Movable Bridge Mechanical Repairs	Repair on moveable parts, repair on engines, gears, or machined parts	Bridge
Movable Bridge Corrective Maintenance	Corrective maintenance-includes electrical repairs	Bridge

2.3.1.2 Rehabilitation

Bridges with one or more component with a GCR that is less than or equal to 4 and a sufficiency rating that is less than or equal to 80 percent are to be subjected to rehabilitation and repair. Sufficiency ratings are determined by the sufficiency rating formula. The sufficiency rating formula ultimately provides a single percentage that reflects the rating of the bridge. A 1oo percent rating would indicate that the bridge of subject is wholly sufficient while a 0 percent rating would indicate that the bridge of subject is wholly deficient. The sufficiency rating formula takes into account the following (Ahmad, 2011)

- Structural Adequacy (S1): S1 takes into account the superstructure, substructure, culvert, and inventory ratings.
- Serviceability and Functional Obsolescence (S2): S2 takes into account rating reductions, roadway insufficiency, and the underclearance.
- Essentiality for Public Use (S3): S3 takes into account the detour length, average daily traffic, and the STRAHNET highway designation.
- Special Reductions (S4): S4 also takes into account the detour length as well as traffic safety features and the structure type of the main span.

The final sufficiency rating (SR) is the sum of S1 through S4 (Ahmad, 2011).

The rehabilitation method is intended for bridges or bridge components that have been rated or deemed to be deficient. Rehabilitation is purposed to remove those aspects catalyzing the deficiency in the bridge structure. Rehabilitation, for example, can consist of the removal and replacement of the deck, superstructure or substructure, the implementation of structures needed to temporarily lessen the magnitude of a deficiency, and even geometric changes to a component of the structure. Funding for the rehabilitation method is subject to HBP funds and therefore the 10 year rule ("VDOT Maintenance and Repair Manual," 2014).

2.3.1.3 Replacement

Bridges with one or more component with a GCR that is less than or equal to 4 and a sufficiency rating that is less than or equal to 50 percent are to be subjected to replacement. The replacement method is defined in the same manner as the rehabilitation in that it is solely concerned with the replacement of structural components or of the bridge itself. Funding for the rehabilitation method is subject to HBP funds and therefore the 10-year rule ("VDOT Maintenance and Repair Manual," 2014).

2.3.2 Joints

Many transportation agencies are currently attempting to reduce the total number of bridge joints in order to reduce the structures' vulnerability to corrosion; however, most bridges in service have joints that are placed at bridge ends and over bearings. Deterioration of bearings and bearing seats below the concrete deck and joints leads to unintended settlement of the superstructure which creates extra stresses within the elements (Purvis, 2003). The deterioration and settlement of the bearing and bearing seats can be due to poor implementation or design of aggregate and concrete, damage due to freezing and thawing, the insufficient implementation of reinforcing steel, and of course the intrusion of water, salts and chemicals leading to corrosion and deterioration of pivotal steel members (Purvis, 2003). Thus, corrosion and deterioration are greatest at joints, due to the fact that joints are the most vulnerable to intrusion when snow and ice are present as well as when deck cleaning is utilized.

In order to minimize the intrusion of water through the bridge deck, the application, rehabilitation, and maintenance of joints and joint seals have proven to be imperative to transportation agencies, which spend millions of dollars to maintain rehabilitate, and replace expansion joints each year. In fact, the NCHRP Synthesis 319

“Bridge Deck Joint Performance, A Synthesis of Highway Practice” found that through a survey of 34 state department agencies and 10 Canadian agencies, all agencies expressed that a preventive bridge maintenance program specifically for joints should be established so that such components can be inspected at more frequent intervals and that such an endeavor, based on their professional opinions, would also be cost effective (Purvis, 2003). The agencies surveyed in the Synthesis 319 report also expressed that decision making with regards to joint implementation, maintenance and repair is done so with a lack of “objective performance data” and that the use of a life cycle cost analysis should begin to be utilized when making decisions with regards to joints (Purvis, 2003). With more informed decision making based on hard and objective performance data, bridge owners would in return be able to make decisions that would result in more efficient practices lowering over costs and impacts of rehabilitation and replacement to themselves as well as the users of the structure.

Based on the NCHRP 319 study, the insufficient frequency at which maintenance actions are provided for joints, and therefore the overall structural health of the bridge, is complimented by a lack of information regarding the life expectancies, operative and overall costs, and the impacts that joint related actions have on BMSs. A life cycle inventory is applicable and imperative to adding knowledge about joint replacement within BMSs to help predict overall costs.

There are an array of differing joint types and joint sealants. Construction joints, or cold joints, are implemented during construction at inflection points between the regions that experience positive and negative flexure. Cold joints are not easily visible and are rarely considered to be a source of leakage (Purvis, 2003). Joints that are usually over expansion bearings, or expansion joints, accommodate deck movements (expansion, contraction, and rotation of the bridge deck). There are a wide array expansion joints that can be characterized as open or closed.

Open joints are not preferred by transportation agencies when compared to closed joints as they provide a passageway that allows for the transport of water and particles from the surface of the deck directly to the critical bridge components beneath it. In order to alleviate the susceptibility of open joints to water and particulate intrusion, closed joints have been implemented. Closed joints are intended to be watertight and are considered to fail when the joint has exhibited leakage, significant physical damage, or has significant damage to the adjacent header.

Another problematic feature of open and closed joints are their armors. The armor is a metallic angle that is installed into the top edges of the concrete directly adjacent to both sides of the joint and is anchored onto the surfaces with either studs, bolts or bars (Purvis, 2003). Thus, installing the angle provides difficulty in that the concrete must consolidate into an appropriate shape to allow the armor to be anchored onto it. The joint armor and its anchorage system, being made of steel, are also susceptible to corrosion, and due to the fact that one side of each individual armor is on the riding surface of the deck, such impacts can lead to dislodgement (at which point the metal becomes a safety hazard), fatigue and the disintegration of the concrete upon which the armor is supported (Purvis, 2003). Armored angles create deterioration to the concrete upon which it is anchored on for both closed and open joints. Thus, it is suggested that;

- The joint system should be installed after the deck is laid.
- A block out is created in the concrete around the joint and is done so with superior concrete or a non-corrosive material (such as a polymer-based material) to support the system (Purvis, 2003).

Agency representatives have expressed that the strip seal joint is favorable for short to medium span bridges while finger joint and modular joint systems are equally favored for long span bridges. Per the suggestions of DOTs, closed joints are favorable to open joints, and will be the subject of this study. Strip seal, asphaltic plug, and compression seal joints are most widely used and therefore are considered in this study of a bridge replacing a cushion seal joint.

According to the NBPP "Survey of Past Experience and State-of-the-Practice in the Design and Maintenance of Small Movement Expansion Joints in the Northeast" (April, 2014), a study that surveyed 28 DOT engineers and maintenance personnel, the majority of those surveyed expressed that when sizing joint sizes and implementing or replacing joints, agencies refer to AASHTO specifications. For endeavors that are not covered by AASHTO, many depend on manufacturer specifications. The NBPP study also showed that most of those surveyed used similar brands of expansion joints. The most common brands used were either D.S. Brown or Watson Bowman Acme (WBA) (Milner & Shenton III, 2014). Thus, manufacturer specifications will also be considered. The range of deck displacement each expansion joint can accommodate through literature searches, referenced throughout this document, were juxtaposed by those from various developers including WBA; it was concluded that the deck displacement ranges did not differ by a significant amount by the manufacturer expectations.

Joints are usually inspected every two years (when the bridge itself is inspected) and all agencies expressed that a preventive bridge maintenance program specifically for joints should be established so that such components can be inspected at more frequent intervals. Most of the agencies also expressed that such an endeavor would be cost effective. Most importantly, the opinion that decision making with regards to joint implementation, maintenance and, repair is done so with a lack of "objective performance data" (Purvis, 2003) and that the use of a life cycle cost analysis should be utilized when making joint rehabilitation decisions.

2.3.2.1 Compression Seals

Compression seals (CS) (shown in Figures 8 and 9) accommodate deck displacement up to 5 to 65 mm (0.25 in. to 2.5 inches) (Taavoni & Tice, 2012). Compression seals are generally regarded as exhibiting good performance for sealing deck joints (Taavoni & Tice, 2012). Initial implementation of the compression seal necessitates, due to deck movement, expansion and contraction, that the joint opening be sized so that such physical changes does not remove the sealant from the deck surface and so that the sealant is not crushed. Compression seals are continuous neoprene elastomeric sections that are rectangular in shape and premolded; however, this sealant is flexible enough that the joint walls do not have to be perfectly parallel or uniform in both the horizontal and vertical directions (Purvis, 2003). Another positive attribute of the compression seal is that they are easy and fast to remove and replace in that a damaged region or portion (that can be properly spliced) can be removed and, after the joint is cleaned, replaced with a new adhesive, the premolded sealant therefore reducing operating costs and traffic closures. The compression seal is collinear with the upper most surface of the roadway, though the top of the seal should be beneath the roadway. Though some transportation agencies prefer the CS, others have expressed concerns with this types of system claiming that such sealants are not dependable as they exhibit a short service life due to their fragility. It has also been reported that one drawback of the compression seal is that, over time, the compression seal becomes brittle; more specifically, during cooler temperatures, when the bridge contracts, the sealant itself may not elastically conform back to its original shape creating tension in the adhesive and causing debonding (Purvis, 2003).

Closed cell (foam) (CCF) and open cell compression seals (OCS) are two types of compression seals. Compression seals are heavily dependent on their adhesive properties as they must stick to the sides of the joints. Both open and closed cell compression seals are able to handle the same amounts of displacement of the structure and the reliability of one type of cell over the other is debatable (Purvis, 2003). Internally, the open compression seal open cell compression seal is porous and has vertical and diagonal neoprene threads as shown in Figure 8. The open compression seal is also to be continuous. The versatility of the open compression seal is a characteristic that is not common amongst most other premolded sealants. According to the NEBPP report of 2014, the open cell compression seals that are applied during new construction and those applied during rehabilitation/replacement actions experience 15 and 6 years of service life, respectively (Milner & Shenton III, 2014). According to the same study, of the Northeastern agencies that responded, approximately 33% of them use CS systems during new construction and approximately 44% use CSs during rehabilitation and replacement actions. Of all of the compression joints employed in the Northeast, the most common closed joint system that is becoming discontinued are the compression seal joints.

Closed cell compression seals, though denser than open compression seals, are still considered to be low in density and can be seen in Figure 9. The 2014 NEBPP reports that CCF joints applied during new construction and those applied during rehabilitation/replacement experience 5 and 2 years of service life, respectively (Milner & Shenton III, 2014). According to the same study, of the Northeastern agencies that responded, approximately 33% of them use CCF systems during new construction and approximately 33% use closed cell compression seals during rehabilitation and replacement actions. Both open cell and closed cell seal types must be sized so that it will fill the available joint opening. Maintenance is provided to the compression seal by sweeping and flushing the joint, and inspection of the seal for cracks and weathering as well as inspection of the armor, keeper bar and all other metallic surfaces (Taavoni & Tice, 2012).

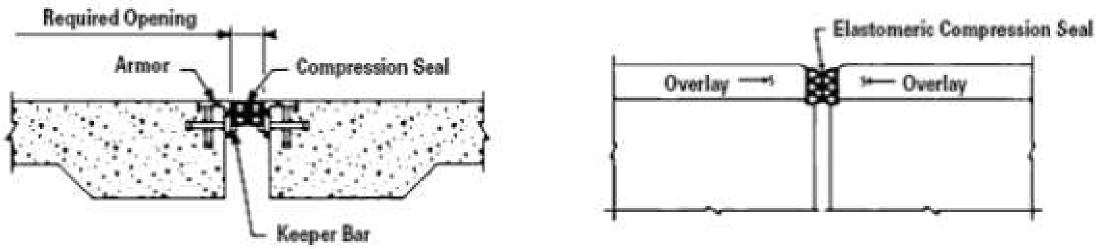


Figure 8: A Typical Open Cell Compression Seal (Taavoni & Tice, 2012)

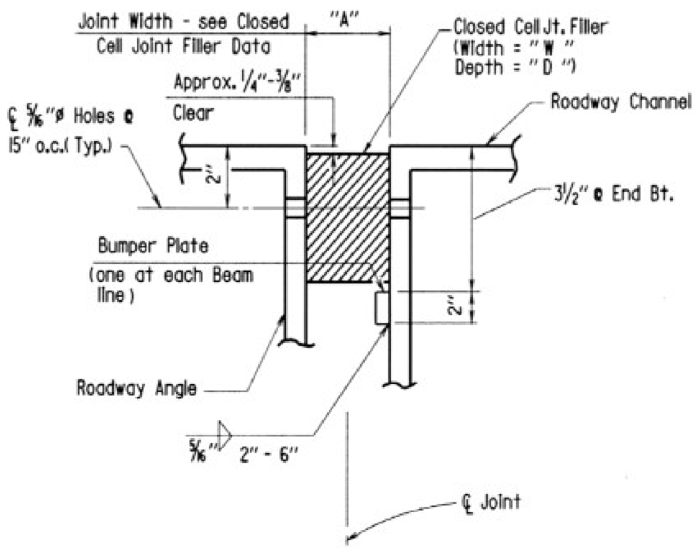


Figure 9: A Typical Closed Cell Compression Seal (Purvis, 2003)

2.3.2.2 Strip Seals

Strip Seals (SS) (seen in Figure 10) consist of a flexible sheet of neoprene that is rigidly attached to the two adjacent joint face armors on both sides of the joint. SSs accommodate displacement up to 100 mm (4 inches) (Taavoni & Tice, 2012) and have very positive reviews amongst agencies that took part in the NCHRP 319 questionnaire and regard SSs to have the longest service life (Purvis, 2003). The seal has an upward concavity when implemented and when the deck is not contracting and it flexes with the corresponding deck displacement (Taavoni & Tice, 2012). Membrane seals, however, are susceptible to tearing (Taavoni & Tice, 2012). Thus, it is important that the seal is sized to compensate for changes in cross sectional area, or obstructions (such as gutter lines), along the joint where the seal is to be implemented, or that the cross sectional area is made uniform. The seal must also be cleaned periodically from debris as upon contraction, non-compressible material held by the seal could eventually puncture the membrane and tear it. Other maintenance practices include reattaching the membrane to edges of the joint, replacing the membrane, and inspecting the joint face armor for deterioration and corrosion.

According to the NEBPP report of 2014, SS joints applied during new construction and those applied during rehabilitation/replacement actions experience 15 and 10 years of service life, respectively (Milner & Shenton III, 2014). According to the same study, of the Northeastern agencies that responded, 100% of them used strip seals for both implementation during new construction and during rehabilitation and replacement actions.

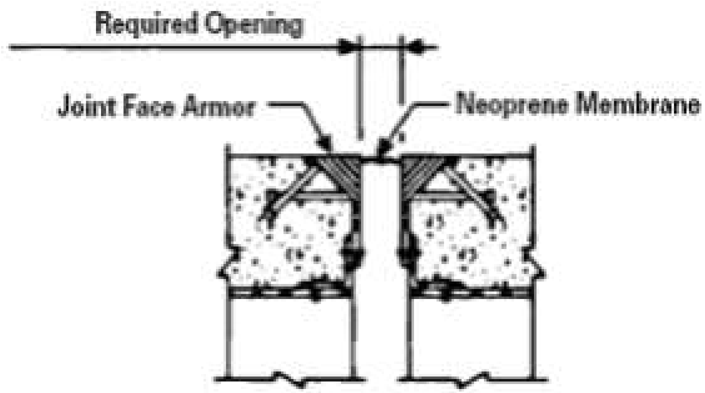


Figure 10: A Typical Membrane Joint (Taavoni & Tice, 2012)

2.3.2.3 Asphaltic Plug Joints

Asphaltic Plug Joint (APJ), or plug joints, are aesthetically and materially similar to the asphaltic material that riding surfaces are often composed of. APJs differ than their seemingly identical counterparts in that APJs are chemically designed to be more elastic (Milner & Shenton III, 2014). APJs are to be used for joints that accommodate deck movements of less than 50 mm (2 inches) (Purvis, 2003). APJs are popular on concrete decks with or without overlays that are being applied. According to the NCHRP 319, the most popular application of the plug joint is when a waterproof membrane is present that has been overlaid with bituminous concrete. All APJs require a blockout that is typically 50 cm (20 inches) wide and 50 mm (2 inches) deep that surrounds the joint. A premolded filler, such as a backer rod, is to be pushed into the joint as well. The premolded filler is to bind to its surrounding joint surfaces and create a truly watertight sealant after a "polymer-modified asphalt binder material" (Purvis,

2003) is poured on top of the backer rod. The asphalt binder is to be heated 370 degrees Fahrenheit. After the material is poured, a steel plate, referred to as the gap plate, is placed on top of the joint crevice partially covering both top sides of the blockout; the gap plate is to be 20 cm (8 inches) wide. The blockout/gap plate surface is then to be covered and the joint is to be filled with an open-graded aggregate “coated with the asphalt binder” (Purvis, 2003) material, i.e. the APJ that is heated to the same temperature as the asphalt binder material placed over the backer rod. A vibrating plate compactor should be employed to assist in consolidating the APJ material until all air voids are filled. The top surface of the APJ, where the material meets the road, should be complimented with an additive for traction purposes.

According to the NEBPP report of 2014, APJs applied during new construction and those applied during rehabilitation/replacement actions experience 10 and 5 years of service life, respectively (Milner & Shenton III, 2014). Positive reactions from agencies concerning APJs is that they are easy to install and repair and thus inexpensive. Also, APJs can be cold-milled and they are not vulnerable to snow plow damages, a catalyst for deterioration for most closed joint systems.

2.3.2.4 Cushion Joints

Cushion joints (CJ) (seen in Figure 11), or elastomeric joints, consist of steel reinforced neoprene that is rigidly attached to both sides of the joint and support displacement up to 100 mm (4 inches) (Taavoni & Tice, 2012). The reinforcing steel plates embedded in the cushion seal makes the seal more durable (Purvis, 2003). The cushions are anchored and held down into the deck with an anchorage system composed of rods, bolts and threads (Purvis, 2003). A cap, applied with an adhesive, can also be utilized to hold down the cushion and seal the anchors as well (Taavoni & Tice, 2012). CJs have lost favor with transportation agencies due to their high implementation and maintenance costs. Cushion joint units are usually provided, in practice, in nominal increments and are therefore subjected to field splicing, especially at curb lines ("Florida Bridge Maintenance and Repair Handbook," 2011). Splicing makes the joint more susceptible to necessary maintenance actions especially during heavy traffic ("Florida Bridge Maintenance and Repair Handbook," 2011). Other concerns regarding cushion joints are that when a part of the joint is damaged, the entire joint system must be replaced, and that cushion sealants must be applied during a specific temperature, otherwise the sealant is not able to fully displace with the structure. The anchorage system must be inspected in order to confirm that the interface between the cushion and concrete is watertight and snug. Other maintenance practices include cleaning and replacement of the sealant and the reinforcing plates.

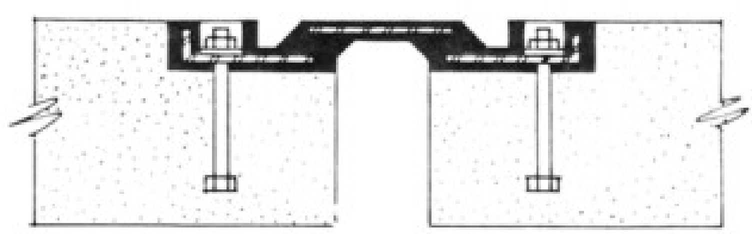


Figure 11: A Typical Cushion Joint (Purvis, 2003)

Chapter 3

METHODS

3.1 Costing

To determine the total costs associated with various joint replacement actions, the owner, user, and the environment costs be determined. Chapter 3 will discuss the calculative methods at which said costs will be determined and the manner at which the LCI will be developed, through on-field observations, to calculate said costs. The factors considered in the calculations will be provided with the intent that such equation will in turn be utilized for simulation purposes as well. Thus, the factors considered in the following equations will determine the type of data to be collected in the case-study and the degree of precision at which they are collected.

The number of workers laboring under a specific task varies throughout the day as does the amount of time spent by crew members providing efficient work. When workers are not laboring, they are assumed to be idling. When workers are idling, the tools and power sources they are using are also assumed to be idling. A crew of workers with a 100% work rate efficiency is not realistic. As will be further expressed in the analysis chapter, the number of workers using a certain machine, or if the machine is idling, effects the fuel consumption and emission rates of said machine. Costs are then simulated through diurnal, material usage, and emission rates collected from the on-field observations. The costing equations must account for the varying degrees of efficiency and the number of workers partaking in the completion of a task. Thus, it is important that relevant diurnal, material usage and emission data that collected are as detailed as possible so that they can be converted to reliable rates, and vice-versa.

For most of the costing parameters, each equation will consider actions that incur costs at the task, stage, and phase levels at which construction activities can be subdivided into. In the following equations, "T" represents a duration, "T_i" represents the durations of a specific task that is being evaluated. Being that there were few tasks that were completed with one team of unchanging personnel, "T_j" represents a segment in time when the workforce laboring to complete a task was uninterrupted, meaning that the number of personnel working on the task was unchanging as was the manner that the task was being worked on.

3.1.1 Agency Costs

The costs incurred to the owner will be based on the wages payed to the workforce, the amount of fuel used by the workforce, and the costs incurred due to material usages. All machinery, generators, and tools will be considered to already have been purchased and owned by the contractor and will not be included in the overall costing incurred to the owner. All owner costs considered are those that are incurred during in-field operations.

3.1.1.1 **Costs due to Wages**

In calculating the costs incurred to the owner, through wages, the number of workers laboring under a certain task must be accounted for, for the entirety of that task's durations. As will be shown in the analysis chapter, the efficiency of the workers involved in a certain task could vary greatly for a number of reasons, one of which is the fluctuating number of workers. By comparing the efficient duration (i.e. with 100% work rate efficiency) and juxtaposing it with the actual duration in the completion of a task, the efficiency rate that best reflects normal working conditions can then be used to rescale the efficient durations to ones that can be expected when simulating.

After the total costs incurred through wages, for the completion of all tasks, are determined, the total cost incurred through wages to complete a , and subsequently, the phase, can then be determined. For example, demolition and construction are two different stages within the joint replacement phase; thus, the sum of the wages of the workforce working on the two separate tasks of breaking the backwall and the deck would equate to the total cost of wages of the dam demolition stage of the joint replacement phase. With,

$OC = Cost\ to\ owner\ incurred\ during\ a\ specific\ phase$

$OCW = Cost\ to\ owner\ due\ to\ workforce\ wages\ for\ the\ completion\ of\ a\ phase$

$S_k = Contributing\ stage\ to\ the\ completion\ of\ a\ phase$

$T_i =$ Specific task

$T_j = Segment\ of\ uninterrupted\ time\ of\ workers\ laboring\ during\ a\ specfic\ duration\ of\ time\ for\ a\ specific\ task\ within\ a\ stag$

$C = Cost$

$L = Number\ of\ Laborers$

$C_L = Cost\ of\ Labor, wage\ of\ laborer\ per\ hour$

$L_{S_{k}T_{j,i}} = Constant\ number\ of\ laborers\ on\ a\ specific\ task\ during\ specific\ stage\ of\ a\ phase$

$D_{S_{k}T_{j,i}} = duration\ of\ efficient\ work\ by\ a\ constant\ workforce\ of\ a\ specific\ task\ during\ a\ specific\ stage\ of\ a\ phase$

Equation 3-1

$$OCW = \sum_{k} \left\{ \sum_{i} \left\{ \sum_{j} \left\{ (C_L) x (D_{S_{k} T_{j,i}}) x (L_{S_{k} T_{j,i}}) \right\} \right\} \right\}$$

3.1.1.2 **Costs due to Fuel Usage**

The costs incurred to the owner through fuel usages can be determined in a similar fashion as the wages. The costs incurred through fuel usages will consider the type of machine that is being used for a specific task, and the continuous duration at which the machine is being used in a particular manner. The fuel-type, rate of fuel consumption, and durations of continuous operating time (i.e. whether the machine is idling, or being used by 1, 2, 3, etc. workers) will all be factors in the following equations and such factors must be sought after during the in-field observations. With,

$OCF = Tota\ \ Cost\ to\ owner\ due\ to\ fuel\ consumption\ for\ the\ completion\ of\ a\ phase$

$C = Cost$

$F = Fuel$

$RF = Rate\ of\ Fuel\ Consumption\ in\ gallons\ per\ hour$

$M_h = Machiner\ \ \ Type$

$OT_{M_h} = Operating\ time\ of\ machinery\ type, M_h$

$C_{F_{M_h}} = Co\ \ \ \ of\ fuel\ for\ machine\ type, M_h$

$RF_{M_h} = Rate\ of\ fuel\ consumption\ of\ specific\ machinery$

Equation 3-2

$$OCF = \sum_{k} \left\{ \sum_{i} \left\{ \sum_{h} \left\{ \left(\ \ _{F_{M_h}} \right) x (RF_{M_h}) x \left(OT_{S_{k T_{i,j}} M_h} \right) \right\} \right\} \right\}$$

3.1.1.3 **Costs due to Material Usage**

When simulating, it is imperative that the rates at which certain materials, or supplies, are applied for differing tasks and structural components are determined. Fuel is not considered a supply-type and thus considered its own category. Due to the wide variety of materials used on the field and the varying ways at which they are applied, it is up to the data collector and those calculating the costs to determine the dependent variable at which the rates of usage amount and cost of the material will be provided. For example, as will be further explained in the analysis section, the rate of water usage for the curing of concrete was determined per hour while the rate of methacrylate usage was determined per linear foot. With,

$OCI = Total\ cost\ to\ owner\ due\ to\ inventory\ acquisition\ and\ usage\ for\ in-field\ operations$

$MU = Magntidue\ of\ usageper\ \ pre-defined\ unit\ of\ inventory\ type$

$CpM = Cost\ per\ pre-defined\ unit\ of\ inventory\ type$

Equation 3-3

$$OCI = \sum_{k}\left\{\sum_{i}\left\{\sum_{j}\left\{(M\quad s_{k\,T_i})x(Cp\quad s_{k\,T_i})\right\}\right\}\right\}$$

3.1.1.4 **Total Owner Costs**

The costs incurred to the owner are all of the costs not incurred by users of the roadway and the environment. Thus,

Where,

$OC = Costs\ Incurred\ to\ the\ Owner$

Equation 3-4

$$OC = OCW + OCF + OCI$$

The owner cost is therefore the costs incurred to the owner through wages, fuel, and materials, all of which are necessary in the completion of the project.

3.1.2 User Costs

Work-Zone Road User Costs (WZ RUC) are those that are incurred to motorists and passengers due to the presence of a work-zone. The WZ RUC will represent the costs incurred to society during on-field construction phases, where society, in the scope of this research, is considered motorists and passengers affected by the work zone. Two general categorical quantities that, due to the work zone, impacts users during construction- the time lost to motorists and the depreciation of the motorists' vehicles. More specifically, societal impacts are based on the costs associated with the lost time to drivers and passengers when traversing the structure with the work-zone present (traveler delay time and cost), when traveling on detours (detour delay time and cost), as well as the expected depreciation from a vehicle (vehicle operating costs) due to the extended time operating on the structure and detours, change in operating speed, and the increase of operating distance when navigating the work-zone and detours (Mallela & Sadavisam, 2011). The vehicle operating costs consider the expected fuel consumption and vehicle degradation of the vehicle and is dependent on the speed at which the vehicles are traveling, the duration of time at which they are traveling, as well as the vehicle type. The time lost to motorists is therefore the sum of the passenger delay time on the structure and the passenger delay time incurred while navigating the detours for all automobiles and freight trucks through the duration of the reconstruction process, while the vehicle operating cost is the sum of the fuel cost and expected vehicle degradation of vehicles navigating the structure and the detours (Mallela & Sadavisam, 2011).

The congestive effect of detouring vehicles on the bypasses are not considered in thus study; the speed limits on the detour components are considered to be the speed at which the detouring vehicles are traveling with uninterrupted flow. Thus, for vehicles using the detour, the increase in distance traveled will affect the costs incurred to the driver and passengers in terms of delay time and vehicle operating distance and speed. The travel delay time and vehicle operating costs incurred to motorists traversing the structure with the presence of a work zone, however, is determined on an hourly basis.

3.1.2.1 **Traveler Delay Time and Costs**

The detour delay time (DDT) and travel delay time (TDT) of each phase are not only dependent on the work zone, detour conditions, volume of vehicles and the operating conditions of said vehicles, but also on the average vehicle occupancy (AVO). Since the TDT and DDT measure the amount of extra time incurred to motorists and passengers due to the presence of a work-zone, the number of passengers and drivers must be determined to scale the lost time incurred to those that are affected by the construction process, this is done by considering the AVO. Freight trucks are considered to have an AVO of 1. The AVO used in the study was determined from the 2009 National Household Travel Survey (NHTS), a survey that gathered personal travel data amongst 150,147 households across the United States (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). The NHTS was funded by the Federal Highway Administration (FHWA). In the NHTS study, AVO’s were found for work, shopping/personal errands, societal and recreational purposes, with an AVO of 1.67 representing all purposes that had a confidence interval of .03 for passenger vehicles (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). Only after the representative TDT and DDT are determined for automobiles and freight vehicles during the construction phases, the travel delay costs (TDC) and detour delay costs(DDC) can be determined.

3.1.2.1.1 Vehicle Delay Time

In the pursuit of fashioning the TDT and DDT equations, the delay of the vehicles traversing the bridge with the presence of the work-zone, and those on the detours must be determined. To determine the vehicle delay on the structure during each weekday and weekend 24-hour period during a particular month and phase, the duration to traverse the structure during normal conditions are found by dividing the bridge length (in miles) by the normal travel speed (in miles per hour). Thus, it is assumed that automobiles and trucks travel at the same speed through the structure with uninterrupted flow. The increase of vehicle duration to traverse the structure with the presence of a work-zone, which will be subject to the costing parameters explained further on, is determined by dividing the structure length by the work-zone travel speed at every hour during each phases of construction and subtracting the normal vehicular travel duration from the work-zone vehicular duration. The increase of vehicle duration to traverse the detours are also found in a similar fashion. Thus, it is also assumed that automobiles and trucks travel at the same posted speed through the detours with uninterrupted flow. Where,

$VD = Vehicle\ delay\ (Vehicle\ per\ hour\ (general))$

$WZ = Work - zone\ identifier$

$DT = Detour\ identifier$

$STL = Structure\ length\ (miles)$

$NTS = Normal\ traffic\ speed\ on\ bridge\ structure (miles\ per\ hour)$

$DTL = Detour\ traffic\ length\ (miles)$

$DNTS = Detour\ normal\ traffic\ speed\ (miles\ per\ hour)$

$WZT \quad = Traffic\ speed\ with\ the\ work - zone\ present\ on\ the\ structure\ (miles\ per\ hour)$

$V = Vehicle\ identifier$

$h = A\ specific\ hour, either\ of\ a\ weekday\ or\ weekend\ of\ a\ specific\ month$

$z =$
$Specific\ component\ of\ detour\ making\ up\ the\ entire\ detour\ length\ of\ a\ specific\ phase$ (detour links)

$TD = Traffic\ direction\ identifier$

$FD = Free\ traffic\ direction\ (with\ partial\ lane\ closure)$

$DD = Detoured, bypassed, traffic\ direction$

$P_n = Phase\ of\ project, determining\ the\ traffic\ direction$

Equation 3-5

$$VD_{WZ} = \sum_{y} \left(\frac{STL}{WZTS_{P_{n}V_{h}}} - \frac{STL}{NTS_{TD_{FD_{V_h}}}} \right)$$

Equation 3-6

$$VD_{DT} = \sum_{z} \left[\sum_{y} \left[\frac{DTL_{P_{n_{d_z}}}}{DNTS_{P_{n_{d_z}}}} - \frac{STL}{NTS_{TD_{DD_{V_h}}}} \right] \right]$$

3.1.2.1.2 Traveler Delay Cost in Work-Zones and Detours

After the vehicular travel delay is determined, the values must then be scaled to represent the incurred time lost to the volume of automobiles and freight vehicles delayed as well as the motorist and passengers within the vehicles. By multiplying the average hourly traffic volume of automobiles and trucks during a particular phase and hour by both the incurred lost vehicular traveling time and by the average vehicle occupancy of the vehicle type the lost time incurred to the motorists and passengers of each vehicle type is determined. By summing the delayed time incurred to motorists and passengers of the automobiles and trucks over the number of hours that comprises of a phase and by summing the lost time over the phases that comprises the project the total amount of lost time to motorists and passengers are determined. The DDT is mathematically determined in a similar fashion as the TDT except that it is determined over all of the links in the detour direction or directions. *The vehicle delay on the detours is summed over the number of hours and detour links that comprises the phase as well as the number of phases that comprises the entire project.* To determine the travel delay costs incurred to travelers traversing the work-zone and detours factors representing the cost of time are to be retrieved. To determine the passenger delay costs on the structure and detours, the VOT costing parameters are to be dependent on whether the passengers are traveling via automobile or truck, at least.

Where,

$TDT = Travel\ delay\ time\ (hour)$

$AVO = Average\ vehicle\ occupancy$

$TD = Travel\ direction\ identifier$

$TD_{\Delta} = Direction\ of\ vehicles\ traversing\ the\ work - zone\ or\ the\ detour(s)(DT\ or\ WZ)$

$V_{\Phi} = Vehicle\ type - Either\ automobile\ or\ truck$

$\Phi_h = The\ AHT\ of\ the\ automobile\ or\ truck\ vehicle\ types\ during\ the\ hour\ of\ "h"$

$CT_{V_{\Phi}} = Cost\ of\ Time\ per\ automobile\ or\ truck$

Equation 3-7

$$TDC = \sum_{n}\left[\sum_{\mathrm{h}}\left[\sum_{\Phi}\left[\sum_{\Delta}\left[\left(\quad {}_{V_{\Phi}}\right)\left(AVO_{V_{\Phi}}\right)\left(AHT_{P_{n_{\Phi_{h_{TD_{\Delta}}}}}}\right)\left(VD_{\Delta}\right)\right]\right]\right]\right]$$

Thus, the total traveler delay time is the total traveler delay time incurred to vehicles traversing the structure in the presence of a work-zone summed with the total traveler delay time of vehicles navigating the detours during all phases of the project until completion. In the previous equations the phase identifier will determine the direction of travel due to the fact that each phase will be assumed to have only one direction of travel as the other direction was closed off; this assumption is based on the case-study that will be further discussed in the LCI section. However, when determining the difference between a travel direction during a specific phase with the conditions before the work-zone was present (i.e. during normal traffic conditions), a different identifier must be used. Thus, when the travel direction variable, or TD, is utilized, it is in reference to the same direction that the phase identifier is referring to. .The total traveler delay cost is the total traveler delay cost incurred to vehicles traversing the structure in the presence of a work-zone summed with the total traveler delay costs of vehicles navigating the detours during all phases of the project until completion.

3.1.2.2 **Vehicle Operating Cost**

To determine the costs incurred to vehicles due to both traversing the structure during the presence of the work-zone and traveling on the detour, costing factors to convert vehicle operations to operating costs must be determined. The operating costs are to be dependent on speed, the vehicle-type, and distance traveled; every speed must be correlated to an operating cost. Thus, the operating distances for both automobiles and trucks must be determined when the work zone is present on the structure, as well as on the detours. The speeds at which the automobile and truck volumes traverse the structures and detours must also be incorporated in the pursuit of determining the total operating costs associated with the durations, work-zone lane closures, and detour lengths of each phase.

3.1.2.2.1 Vehicle Operating Cost in Work Zone and Detours

Due to the differences between detour characteristics per phase, more specifically the changing lengths and speed associated with each phase's unique detour and its comprising links the vehicle operating costing equations will differ between work-zones and detours, just as they did for the delay times for both route types. To account for distance, expressed as the structure length in the COV_{WZ} equations, the detour lengths will be expressed as the sum of each detour's link lengths associated with a particular phase.

Where,

Equation 3-8

$$STL_{DT} = \sum_{n} \left[\sum_{z} \left[DTL_{P_n d_z} - STL \right] \right]$$

To determine the automobile and truck operating costs in the work zone and detours, the operating costs under normal conditions on the structure must be subtracted by the induced operating costs due to the work-zone both on the structure and on the detours. To determine the operating costs, the AHT must be multiplied by the structure length (which does not change regardless of the presence of the work-zones), the detour length, and the induced speed and distance changes due to the presence of the work-zone. By summing the vehicle operating costs for the total number of hours, the magnitude of the cost fluctuating depending on the month, time of day, and the type of day, over all phases of construction, the total operating costs of all vehicles traversing structure is determined. Note that for vehicle traversing the detour(s), the detour travel speed, as previously mentioned, is considered the normal travel speed, regardless of the work-zones effect on said roadways, due to the fact that the congestive effect of detouring vehicles on the bypasses are not considered in this study.

Where,

$COV = Monetary\ value\ of\ operating\ vehicle$

$NC = Normal, none\ work - zone\ conditions$

$SPD = Travel\ speed, on\ identified\ bridge\ or\ detour, during\ work - zone\ presense$

$FD = Free\ traffic\ direction\ allowed\ to\ traverse\ work - zone$

Equation 3-9

$$COV = \sum_{n}\left[\sum_{h}\left[\left[\sum_{\Phi}\left[\sum_{\Delta}\left[\left(AHT_{P_{n_{\Phi_{h_{D_{\Delta}}}}}}\right)\left(OV_{P_{n_{SPD_{h_{V_{\Phi_{D_{\Delta}}}}}}}} - OV_{TD_{FD_{NTS_{h_{V_{\Phi}}}}}}\right)(STL_{\Delta})\right]\right]\right]\right]\right]$$

Thus, the vehicle operating cost is the vehicle operating costs incurred to vehicles traversing the structure in the presence of a work-zone summed with the total vehicle operating costs of vehicles navigating the detours during all phases of the project until completion.

3.1.2.3 **Total Road User Cost**

With the work-zone and detour passenger delay and vehicle operating costs determined, the total road user costs can be established by summing all delay and vehicle operating costs on all routes. Thus where,

$RUC = Road\ User\ Cost$

Equation 3-10

$$RUC = T \quad _{WZ_{Au}} + TDC_{WZ_{Tr}} + TDC_{DT_{Au}} + TDC_{DT_{Tr}} + COV_{WZ_{Au}} + COV_{WZ_{Tr}} + COV_{DT_{Au}} + COV_{DT_{Tr}}$$

$$Or,$$

Equation 3-11

$$RUC = TDC + CO$$

3.1.3 Environmental Costs

The environmental impacts that construction activities, as well as their corresponding work-zones, have on the environment can be measured by determining the emissions from the various motor driven tools being used on the site, as well as determining the increase in emissions from vehicles both traversing the work-zone and circumventing it on detours. The incurred environmental impact of the work-zone due to vehicles traversing the structure and those on the detours must be accounted for because any obstacle that changes the traveling time, or even the manner at which the vehicle travels, would have an effect on the emissions expelled by said vehicle. An inventory of all environmental emission factors must be established for the wide array of motor driven tools, generators, and vehicles; based on the duration and the manner at which the motors are being used, volumes of expelled pollutants can then be estimated throughout each task, stage, phase, and when idling. Based on the volumes of each emitted pollutant by the various motors associated with the work-zone, such volumes must be monetized in order to provide a nominal value of the impact that such on-field activities have on the environment. After the emission rates are determined, they will be converted into total volumes corresponding to tasks, stages and phases of the project that will then be converted into costs so as to determine the amount of the impact such joint maintenance and construction operations have on the environment.

3.1.3.1 **Non-Vehicular Emissions**

In the case-study, as will be further explained, it was determined that all of the motor driven tools were either connected to an air compressor, electric generator, or functioned independently of a shared power generating unit. The electric generator was used for smaller electric tools such as such grinders, saw and drills that would connect to the electrical outlets provided by the generator. The air compressor provides compressed air for the breakers, airblasters, sandblasters, and silicone applicators that in turn powers the aforesaid tools. In general, there were only three motor driven tools that were not connected to any power source, the skid steer loader, the aforesaid engine driven welder, and the hand held concrete saws. The skidder was used for breaking, cleaning, and moving heavy objects while the concrete saw was used for sawing and cutting of the deck and parapet overlay and reinforcement beneath them.

The EPA's Office of Transportation and Air Quality (OTAQ) has developed a Motor Vehicle Emission Simulator (MOVES). MOVES estimates emissions for both on-road and non-road mechanical engines. The MOVES software provides emissions factors that assists in the development of the emission rates and ultimately the amount of emissions expelled into the air. The emission factors for equipment such as the air compressor is determined by the equipment type, horse-power, fuel type, location, date, and time of day. The equipment is organized into 12 subdivisions such as agriculture, commercial, construction, industrial, recreational, and so on. The emission rates outputted, depending on how the user wants the outputs reported, in this effort, are in g/hp-hr and provides factors for various equipment for carbon monoxide, nitrogen oxides, ammonia, sulfur dioxide, greenhouse gases, PM10 and PM2.5. An example of the MOVES outputs for the skid steer loader and the emission rate constants produced for the machine is shown in Table 12 below

Table 12: Example of the MOVES Software Output

MOVES RunID	County	Sector	Year	Month	Day	Fuel	Fuel	Pollutant	Pollutant	Process	Equipment Description			hp ID	hp Bin					Emission Rate (g/hp-hr)
1	10001	2	2015	7	5	2	Diesel	2	Carbon Monoxide (CO)	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	5.938813
1	10001	2	2015	7	5	2	Diesel	3	Oxides of Nitrogen (NOx)	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	5.514472
1	10001	2	2015	7	5	2	Diesel	30	Ammonia (NH3)	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	0.005643
1	10001	2	2015	7	5	2	Diesel	31	Sulfur Dioxide (SO2)	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	0.004471
1	10001	2	2015	7	5	2	Diesel	90	Atmospheric CO2	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	692.2916
1	10001	2	2015	7	5	2	Diesel	100	Primary Exhaust PM10	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	0.896772
1	10001	2	2015	7	5	2	Diesel	110	Primary Exhaust PM2.5	1	Skid	Steer	Loaders	75	50	<	hp	<=	75	0.869869

As can be seen in Table 12, the emission rates are provided in g/hp-hr; thus by logging the durations at which the machine is being used and its horse-power, the volume of pollutants can be determined. To mathematically express how each tool observed on the field will contribute to the total emitted pollutants and overall environmental impact, a brief description of each mechanical tool and/or power source must be provided, to understand the role that allocations plays in said calculations.

Generally, the motor driven tools that are subject to allocation and those that are not can be expressed in two general equations. Note that for tools that are subject to allocation, where a specific number of usages are known of the aforesaid tools, the number of laborers are accounted for in the scaling allocation constant. The allocation constant, "A", will be unique to each power source and will scale the volume of the emitted pollutants. When allocation is not applicable, the number of tools being used "Q" must be accounted for. However, for each tool type, regardless if it is subject to allocation or not, must account for the emissions expelled by the specific machine as well as the emissions expelled by the machine, or its power source, when idling. Thus, for specific tools that are allocated and for those that are not, the general relationship stands in determining the direct emissions, over a task, stage, and the phase in equation . Thus, for tools that are not subject to allocation, such as the power driven welder and the electric driven tools, the number of possible allocations for a particular power source, "ξ", and the allocation constant, "A", will become zero as the number of a specific tool being used at once, "Q", will take on a specific number greater than or equal to one. For tools that are subject to allocation, such as the breakers, abrasive blasters, air blasters, and skid steer loader, "ξ" and "A" will take on specific values greater than or equal to one while "Q" becomes zero, since the number of tools utilized in each associated allocation is already accounted for the in the allocation constant.

Where,

$E_{NV_\lambda} = Direct\ power - source, non - vehicular\ emissions$

$\mu = Power\ source\ or\ motor\ driven\ tool\ \ signifier$

$D = Duration\ of\ effective\ labor$

$\xi = Number\ of\ specific\ allocations$

$E = Emissions\ signifier$

$E_x = Specific\ pollutant\ type\ signifier$

$R_{E(\mu)_x} = Emission\ rate\ of\ specific\ emitted\ pollutants\ associated\ with\ power\ source\ allocations$

$A_{T(\mu)_j} = Allocation\ constant, sccaling\ the\ emission\ rate\ to\ the\ correct\ usage\ of\ the\ power\ source$

Equation 3-12

$$Direct\ Power\ Source\ Emissions\ (E_{NV_\lambda}) = \sum_n \left[\sum_k \left[\sum_x \left[\sum_i \left[\sum_{j=1}^{\xi} \left[\left[\sum_\mu \left[\left(D_{P_{n_{S_{k_{T(\mu)_{i,j}}}}}} \right) \left(R_{E(\mu)_x} \right) \left(A_{T(\mu)_j} + Q_{P_{n_{S_{k_{T(\mu)_{i,j}}}}}} \right) \right] \right] \right] \right] \right] \right] \right]$$

Idling of the power-sources are to be considered as unique tasks. Thus, the air compressor itself creates emissions when not being used (idling), which must also be accounted for. Thus, the generator itself creates emissions, when not being used (idling), which must also be accounted for. To account for the idling emissions of the power source, the idling emissions of each pollutant type due to the time when the generator was on but efficient work was not occurring ($\boldsymbol{E_{NV(\iota)}}$)must be determined. Note that the number of laborers are not accounted for the emissions, because the laborers are accounted for in the allocation constant.

$\Upsilon = Power\ source\ of\ specific\ motor\ driven\ tool, \mu$

H
$= Total\ amount\ of\ specific\ work\ hours\ where\ the\ generator\ was\ left\ on\ (idling\ or\ in\ use) during\ each\ day\ (date\ dependent)$

d
$= Duration\ of\ efficient\ and\ constant\ work\ on\ a\ task\ during\ a\ stage\ of\ a\ phas\ \ while\ all\ using\ one\ specific\ tool\ in\ crew\ hours$

$R_{E(\mu(\iota))_x} = Idli\ \ \ \ emission\ rate\ of\ power\ sources\ for\ specific\ emitt\ \ \ \ pollutants$

Equation 3-13

$$Idling\ Power\ Source\ Emissions\ (E_{NV_\iota}) = \sum_n \left[\sum_k \left[\sum_x \left[\sum_i \left[\sum_{j=1}^{\xi} \left[\left[\sum_\mu \left[\left(H_{P_{n S_k}} - d_{P_{n S_{k_{T(\mu)_{i,j}}}}} \right) \left(R_{E(\boldsymbol{\alpha}(\iota))_x} \right) \right] \right] \right] \right] \right] \right] \right]$$

Thus, the total volume of pollutants emitted in the model can be determined by summing the direct and idling power source emissions throughout all tasks, stages, and phases considered.

Equation 3-14

$$E_{NV} = E_{NV_\lambda} + E_{NV_\iota}$$

Or,

Equation 3-15

$$E_{NV} = \sum_n \left[\sum_k \left[\sum_x \left[\sum_i \left[\sum_{j=1}^{\xi} \left[\left[\sum_\mu \left[\left(D_{P_{n S_{k_{T(\mu)_{i,j}}}}} \right) \left(R_{E(\mu)_x} \right) \left(A_{T(\mu)_j} + Q_{P_{n S_{k_{T(\mu)_{i,j}}}}} \right) + \left(H_{P_{n S_k}} - d_{P_{n S_{k_{T(\mu)_{i,j}}}}} \right) \left(R_{E(\boldsymbol{\alpha}(\iota))_x} \right) \right] \right] \right] \right] \right] \right] \right]$$

3.1.3.2 **Vehicular Emissions**

From determining the road user delay costs, the speeds and durations incurred to vehicles and its passengers have been simulated for vehicles and trucks traversing the structure during the work zone and for those on the detour. There are two types of models that can be used to determine emission factors from vehicle- the static model and the dynamic model (Mallela & Sadavisam, 2011).

Static emission factor models provide emission factors for each specific type of pollutant considered, at varying speeds for automobiles and trucks. Static models for determining emission factors are appropriately utilized for estimating the volume of various emitted pollutants "for long-scale planning studies where the estimations based on average speed are highly accurate; however, these models are not sensitive enough to capture the actual driving conditions such as acceleration, deceleration, idling, and cruising cycles in a work zone" (Mallela & Sadavisam, 2011), factors that were also not considered when determining the road user delay costs. Dynamic emission factor models necessitate precise traffic collection data at the exact location of the work zone in order to correctly captures the acceleration, deceleration, idling, and cruising cycles due to the work zone and traffic signals. Referring back to the road user delay costs, time lost to acceleration and deceleration as well as traffic conditions such as shock waves and signal delay time are not considered. Thus, the work zone and its impact on vehicular emissions (both on the detour and on the structure) will be subjected to a model, like the road user delay costs, that utilizes such assumptions. Thus, a static model will be utilized for determining the environmental impact of vehicles on the structure, traversing the work zone and for those on the detour.

A static emission factor model suggested by the Federal Highway Administration's "Work Zone Road User Costs- Concepts and Applications" of December 2011, is Mobile 6.2 (now MOVES) which is used by most states, though specifically not by California as they have their own model, which is also recommended by the document (Mallela & Sadavisam, 2011). The Emission Factor (EMFAC) model is developed by the California Environmental Protection Air Resource Board (CARB) and is used as a mobile vehicle emission estimation tool ("Mobile Source Emission Inventory -- Categories," n.d.). An example of the 2003 EMFAC model, provided by the aforementioned "Work Zone Road User Costs- Concepts and Applications" book is shown below in Table 13).

Table 13**:** Statics Emission Model for Automobiles and Trucks Dependent on Traveling Speeds (Mallela & Sadavisam, 2011)

Speed (mph)	Auto (g/mile)					Trucks (g/mile)				
	CO	NO R X	PM R 10	SO R X	VOC	CO	NO R X	PM R 10	SO R X	VOC
5	16.97	1.39	0.1	0.01	1.97	31.44	16.57	0.71	0.12	3.6
10	14.25	1.21	0.07	0.01	1.48	26.81	15.19	0.63	0.12	3.18
15	12.23	1.07	0.06	0.01	1.18	20.51	13.11	0.51	0.11	2.58
20	10.79	0.97	0.05	0.01	0.99	16.68	11.7	0.42	0.11	2.19
25	9.75	0.9	0.04	0.01	0.88	14.29	10.8	0.36	0.11	1.93
30	8.98	0.86	0.04	0	0.8	12.78	10.28	0.31	0.11	1.74
35	8.42	0.83	0.04	0	0.75	11.83	10.08	0.28	0.11	1.62
40	8.02	0.81	0.03	0	0.72	11.27	10.18	0.25	0.11	1.53
45	7.77	0.81	0.03	0	0.71	11	10.59	0.23	0.11	1.47
50	7.66	0.82	0.03	0	0.7	10.98	11.35	0.22	0.11	1.42
55	7.71	0.84	0.03	0	0.71	11.19	12.54	0.21	0.11	1.4
60	7.97	0.88	0.03	0	0.73	11.69	14.3	0.2	0.11	1.38
65	8.51	0.94	0.03	0	0.76	12.55	16.87	0.2	0.11	1.38

To determine the volume of each pollutant emitted by the vehicles, the average hourly traffic of both trucks and automobiles traversing the work zone, and on the detours, for each phase, must be considered. By multiplying the AHT determined for the road user costs, and by considering the speeds and distances associated with traversing the work zone and the detours of each phase, with the emission constants provided, the total volume of each emitted pollutant can be determined.

3.1.3.2.1 Vehicular Operating Emissions in Work-Zone and Detours

Where,

$E_v = Induced\ emissions\ of\ vehicles\ on\ bridge\ and\ detour\ structures\ throughout\ phase\ (g)$

$SPD = Trave\ \ speed, on\ bridge\ or\ detour(s), during\ work - zone\ presense$

Equation 3-16

$$E_V = \sum_{n} \left[\sum_{h} \left[\sum_{x} \left[\sum_{\Phi} \left[\sum_{\Delta} \left[\left(AHT_{P_{n_{\Phi_{h_{D_\Delta}}}}} \right) \left(R_{E_{x P_{n_{SPD_{h_{V_{\Phi_{D_\Delta}}}}}}}}} - R_{E_{x TD_{FDNTS_{h_{V_\Phi}}}}} \right) (STL_\Delta) \right] \right] \right] \right] \right]$$

3.1.3.3 **Costing of Emissions**

Though there is no general unanimity as to how to monetize environmental impacts due to emitted pollutants, several attempts have endeavored to do so. Resources that monetize the environmental impacts of emissions are done so by studying and appropriating studies to determine the general health impact incurred to the populace due to emissions and the associated costs gained to the those that have had their health affected by such adverse conditions (Mallela & Sadavisam, 2011). Thus, in urban areas where the population is more densely collected, the costs associated with pollution would be higher than similar emission volumes were they expelled in a less densely populated suburban area. Two resources suggested by the FHWA's "Work Zone Road User Costs- Concepts and Applications" of December 2011, are The Highway Requirements System-State Version (HERS-ST) 2005 Technical Report, and estimates by the California Department of Transportation (Caltrans) (Mallela & Sadavisam, 2011).

3.1.3.3.1 Non-Vehicular Operating Costs

Utilizing the motor driven tool emissions previously established, the costs of such tools can be determined. The costs, despite which tool or generator was being used, is constant. The impact of the cost is scaled due to the emission rates and durations which are specific to the aforesaid parameters.

Where,

$CE_x = Monetary\ value\ of\ speciffic\ emission\ type\ x$

$CE_{NV} = Total\ monetary\ value\ of\ non - vehicular\ power\ driven\ tool\ emissions$

Equation 3-17

$$CE_{NV} = \left\{ \sum_x [CE_x] \right\} E_{NV}$$

3.1.3.3.2 Vehicular Operating Costs

Utilizing the same tabulated emission costing values, the environmental monetary impact can also be deduced. Life the non-vehicular approach to costing, to determine the cost of the vehicular impact to the environment, the equations expressing the total volume of pollutants emitted by the vehicles will be multiplied by the costing constants where appropriate.

Thus, the total pollutants emitted due to vehicular transport is the sum of the increased pollution of vehicles traversing the work zone and the detours, and can be expressed as so.

Equation 3-18

$$CE_V = \left\{ \sum_x [CE_x] \right\} E_V$$

3.1.3.4 **Total Environmental Impact**

3.1.3.4.1 Total Project Environmental Impact of Emissions

Thus, the total emission considered in this study are those contributed by vehicles (automobiles and trucks) as well as motor driven tools. Thus, the total emitted pollutants are the sum of all of the previous emission equations, which can simply be expressed as

Equation 3-19

$$E = E_{NV} + E_V$$

3.1.3.4.2 Total Project Environmental Cost

Likewise, the total monetary impact of all motor driven entities to the environment can be expressed as

Equation 3-20

$$CE = CE_{NV} + CE_V$$

3.2 Life Cycle Inventory

In the pursuit of simulating the all-encompassing costs associated with different expansion joint replacements, it was imperative that an actual on-field operation be shadowed to gather all of the necessary data so as order to construct an inventory. The duration, material consumption, and emission rates associated with the demolition, cleaning and construction processes were gathered so that they can be used for simulation purposes. Through all stages of the operation, the duration and personnel laboring to complete a specific task were recorded as well as the idling time of workers and machinery associated with the task. Along with the durations associated with each task, the amount of fuel and materials used to complete such a task were also recorded for that component of the bridge. Each component of the bridge was also studied to determine how its geometric characteristics would affect said rates in the completion of a task. With a greater variety of tasks and materials observed, a larger variety of rates can be utilized to simulate a larger variety of tasks; the degree and applicability of a LCA is only as great as the vastness of the assembled inventory. In the pursuit of simulating durations, rates, and material usages of various construction operations it is imperative that a case study is chosen that encompass relatively similar steps (at varying scales) to those of other joint reconstruction operations, in turn providing the initial steps of simulating the owner, user and environmental costs associated with different joint replacements.

3.2.1 Case Study Location and Time

The bridge, being that it is considered a state highway, is owned by the State Highway Agency of Delaware and the agency is responsible for the maintenance of the structure. The toll-free bridge is inspected every 24 months and was last inspected on February of 2013. Edgemoor Road services interstate 495 (I-495) and highway route 13 (US-13). The dimensions of the bridge are pivotal in determining the duration rates associated with the demolition, cleaning and construction stages as well as the total material usages necessary to complete said tasks. Before tabulating all relevant dimensions, a brief discussion of the bridge will be provided. Supplementing the description provided below is Figure 12.

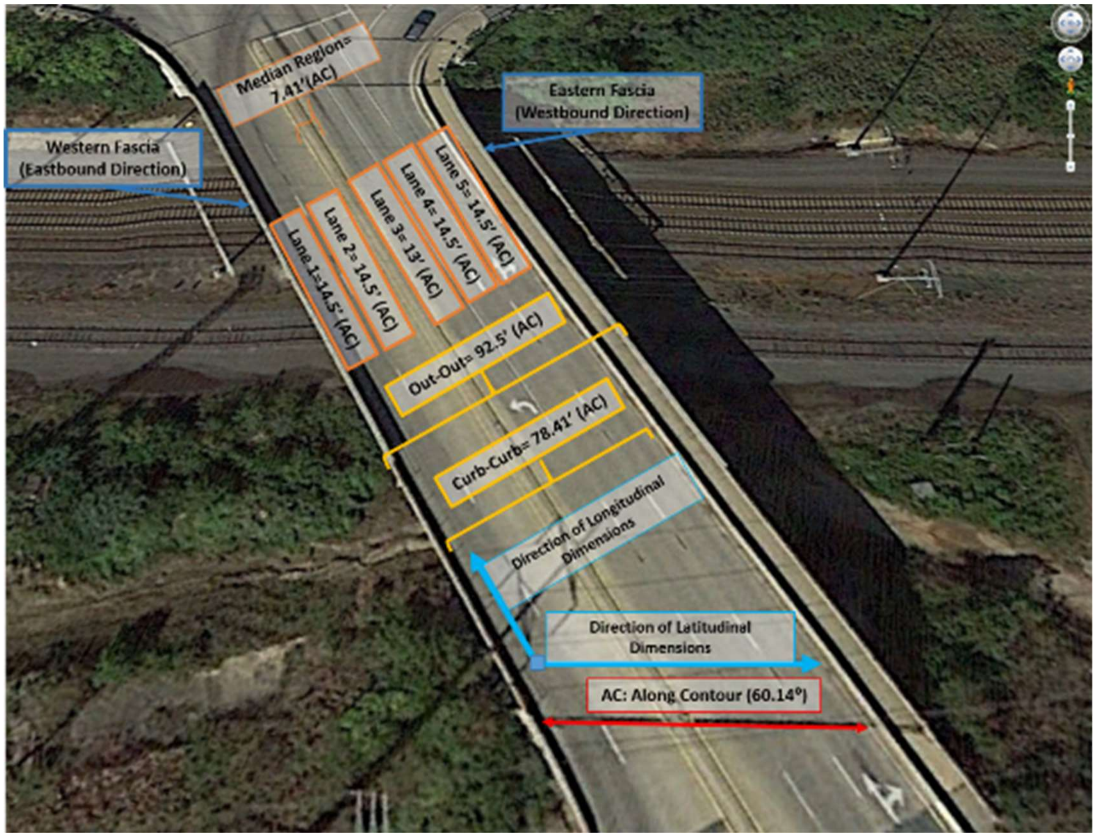


Figure 12: Edgemoor Road over Amtrak and Norfolk Southern; Latitudinal Dimensions, Pre-Construction

As determined by the FHWA NBI, and verified through on-field inspection, the kind of material and design of the superstructure is defined to be composed of steel and continuous stringer/multi-beam girders. The deck structure is composed of cast-in-place concrete, with epoxy coated steel reinforcement. The type of wearing surface of the deck is an integral concrete (separate non-modified layer of concrete added to the structural deck) with no riding surface membrane.

The bridge carries two-way traffic designated as the eastbound and westbound direction, extending from the southern abutment to the northern abutment. The designated eastbound traffic direction consists of two lanes that span the western side of the bridge; the westbound traffic direction, spans the eastern side of the bridge, and consists of three lanes. The lane that is adjacent with the eastbound direction road parapet is designated as Lane 1, while the lane that is adjacent with the westbound direction of traffic is designated as Lane 5. The eastbound and westbound traffic directions are divided by a closed, mountable median, where the roadways are characterized by a 2% grade both sides of the median. The western fascia of the bridge consists of a road parapet. Along the eastern side of the bridge a sidewalk is enclosed by a traffic and pedestrian parapet. The bridge consists of a 30° skew, and does not have any flare and the two abutment joints of the bridge are contoured by 60.14° to the through traffic. The bridge is composed of 3 main spans with no approach spans. The three spans structurally support the 264.5-foot roadway, along the centerline of the bridge, between the two abutment joints.

Being that the on-field operations were focused on full and partial depth demolition and construction actions, it is imperative that all latitudinal dimensions described in the following paragraphs are denoted as “normal” or “along the contour” (AC), since the joints are placed along a 60.14° contour on the bridge. For example, the width of the roadway on the southern edge of the bridge upon which the southern abutment joint that is subject of phase 1 and 2 is 68 feet, but along the contour the length of the joint is 78.417 feet. When finding the all rates associated with the phase 1 joint removal, the length of the joint along the contour will be of importance, and all dimensions recorded to be lateral measurements should be assumed to be along the contour. while the normal length will be documented for the sake of completeness when describing the characteristics of the bridge.

The following dimensions were determined and provided in Table 14 through on-field observations. Within Table 14, note that out-to-out dimension is the distance between the eastern and western fascia, the curb-to-curb dimensions is the distance between the road-side faces of the eastbound direction's road parapet and the pedestrian parapet, and the joint reservoir designation represents the reservoir between the armored headers where the strip seal extrusion is visible. All lengths were categorized as longitudinal, lateral, or depth, and all dimensions recorded in the following Tables are only relevant to the southern abutment joint of the bridge.

Table 14: Tabulated Dimensions of Relevant Bridge Components Recorded During Case-Study

Bridge-Side (E, W) or Bridge End (N, S)	Traffic Direction	Dimension	Along Contour or Parallel	Component	Magnitude	Units
All	All	All	All	Contour	60.14	Degrees
All	All	Long	NA	Structure Length	264.50	ft
N	All	Long	NA	Span 1	100.00	ft
M	All	Long	NA	Span 2	89.50	ft
S	All	Long	NA	Span 3	75.00	ft
E	W	Lat	AC	Overhang	3.32	ft
W	E	Lat	AC	Overhang	3.32	ft
All	All	Lat	AC	Out-Out	92.25	ft
All	All	Lat	AC	Curb-Curb	78.41	ft
All	All	Lat	AC	Median Region	7.41	ft
W	E	Lat	AC	Curb-Median	29.00	ft
E	W	Lat	AC	Curb-Median	42.00	ft
All	All	Lat	AC	Total Roadway	71.00	ft
W	E	Count	NA	Lanes	2.00	-
E	W	Count	NA	Lanes	3.00	-
W	E	Lat	AC	Ln 1	14.50	ft

W	E	Lat	AC	Ln 2	14.50	ft
E	W	Lat	AC	Ln 3	13.00	ft
E	W	Lat	AC	Ln 4	14.50	ft
E	W	Lat	AC	Ln 5	14.50	ft
W	E	Lat	AC	Road Parapet	1.92	ft
E	W	Lat	AC	Road Parapet	1.15	ft
E	W	Lat	AC	Pedestrian Parapet	1.54	ft
E	W	Lat	AC	Walkway	9.22	ft
All	All	Long	AC	Joint Reservoir	0.19	ft

3.2.2 Case-Study Deliverables

From the on-field observations the replacement of the Southern abutment of Edgemoor road can categorized into the three stages of construction, cleaning, and demolition. Construction of the new strip seal joint occurred after demolition was complete while cleaning activities occurred intermittently between both stages. Table 15 reflects the durations of the demolition and construction stages during phase 1 that were included in this study. It should be noted that work was neither done on weekends nor on rainy days and work hours usually ranged between 7:30 AM to 3:30 PM, and during days that rained.

Table 15: Start, End, and Total Duration of the Case-Study Demolition and Construction Stages

Stage	Start Date	End Date	Total Duration (Days)
Demolition	7/30/2015	8/6/2015	7.00
Construction	8/6/2015	8/25/2015	19.00

The total amount of time spent (in worker-hours) to complete the case-study and its three stages are represented in Table 16. A comparison between effective time, idling time and billable time will be provided in the owner, societal and environmental results and costing sections as the differences between effective time and non-effective time effects each of the previously mentioned three pillars.

Table 16: Total Worker-hours Contributed to the Demolition, Construction, and Cleaning Stages

Stage	Total Effective Duration (Worker-hours)	Percentage of Total Time
Total Duration	232.51	-
Demolition	62.10	25.77
Construction	127.38	52.85
Cleaning	43.02	17.85

Edgemoor Road was not only subject to the southern joint replacement. The following were other maintenance activities witnessed on the Northern end of the bridge during Phase 1 on the eastbound direction lanes as they were closed. Though all tasks that were observed on the bridge were recorded, they have not been implemented into this study.

- Partial depth removal and replacement of the backwall of the Northern abutment joint with concrete
- Partial depth removal and replacement of a section of the approach with hot mix asphalt
- Removal and replacement of the epoxy and backer rods between the parapet and the riding surface between the backwall and approach

Phase 1 of southern expansion joint replacement consisted of the following deliverables in order of completion

- The simultaneous demolitions of
    - Providing a full depth removal of the deack and backwall concrete headers, forming the dam blockout
    - Along the backwall and deck headers, remove the traffic parapet and partially remove the wingwall supporting said parapets

- The simultaneous construction of the strip seal joint system and the steel reinforcements pertaining to both sides of the dam, and of the wingwall and parapet
- The construction of formwork within the parapet and wingwall system and the dam prior to the pouring of Class A concrete
- Pouring and treating of the concrete in the dam, wingwall and parapet

Figure 13 depicts the main components of the bridge subject to the demolition and reconstruction. Figure 14 depicts the wingwall, underneath the demolished parapet that was to be demolished. The relevant dimensions associated with the demolition of the dam and parapet are provided in

Figure 13: Components Associated with the Replacement of the Southern Abutment Joint Post-Construction

Figure 14: Wingwall, indicated by the Spray-Paint, to be demolished

All tasks associated with the demolition, construction, and cleaning stages have been described in Appendices A, B, and C, respectively. In Appendices A, B, and C, step-by-step procedures and commentary are provided for all tasks taken in the pursuit of completing each stage. Along with the procedures and commentary, the durations to complete said tasks and the rates of completion and material usages are also tabulated and further explained for each task's respective appendix.

Chapter 4

ANALYSIS

4.1 Cost of Case Study

Utilizing the methods chapter, the analysis chapter will provide readers with the total costs from the case-study, optimized and simulated costs based on the case-study data, and finally the optimized joint maintenance program.

The total costs incurred through the case-study were considered to those incurred to the owner, society, and environment. The owner costs include all costs incurred to the contractor for replacing the expansion joint headers and sealant. The user costs are those incurred through users of the roadway due to increases in lost time and vehicle operating costs. The environmental are those incurred through on-site machinery and changes in vehicle transportation patterns. This section will expand upon the methods section; the readers will be provided with information regarding how the data necessitated by the methods section was attained, how and why they were manipulated, and the costing results.

4.2 Owner Costs

4.2.1 Wages

On a daily basis the time that the crew members arrived on the field to the time that they left were recorded as were the number of crew members that were on the field and for how long, and, as previously mentioned, the tasks that each worker was laboring under and how much of that time was spent efficiently working and not idling. In most cases the crew members that arrived in the morning stayed for the duration of the day, though there were cases when crew members were sent to other jobs. Thus, in terms of wages, the costs incurred to the owner were calculated by how many hours each worker would charge to Edgemoor Road, within the time span of arriving on the field and when the workers left the field. For example, if a worker labored on Edgemoor Road for three hours, then left to attend a job elsewhere, in a different location, three hours of work (wages) would only be considered as the wages costs incurred to the owner for Edgemoor Road. Before determining the total wages paid by the owner, the hourly rate received by the workers must be established. There were five types of workers on the field during the operation

- Traditional Laborer (l),
- Workers Interchanging as Skid-steer Loader Operator (p),
- Carpenters (ca),
- Foremen (f), and
- Contracted Workers (co).

Laborers of all levels interchangeably operated the skid steer loader; thus, tasks dependent on the skid steer loader were not considered to be done by a power equipment operator. Wages were prescribed to each worker based on his title. Foremen and carpenters were paid the same wages, as both were generally responsible for oversight as well as each worker's individual skill set, and interchanged roles based on different operations. The cost of contracted work will not be calculated in the following costs incurred to the owner. The wage-type for each worker is determined in Appendix D.1.

Thus the following workers are associated with the following wages provided in Table 17. The total cost of wages incurred to the owner was $19,645.16.

Table 17: Wages, hours, and % of wages by labor type

Labor Type	Wage ($/Hr)	Total Hours	Total Wages Cost	% of Total Wages
Foreman (f) [Supervision]	43.15	117.52	5070.84	25.81%
Laborer (l)	33.01	403.88	13332.22	67.87%
Carpenter (ca)	43.15	16.3	703.35	3.58%
Skidder Operator (p)	33.01	14.32	472.59	2.41%
Welder (w)	43.15	1.53	66.16	0.34%
Sub-Contracted Work (co)	not included	not included	not included	not included
Totals		553.55	19645.16	100%

Workers are paid whether they are working effectively or not (idling), which can be thought of as work efficiency. It was assumed that the foreman provided 100% work efficiency, due to fact that the efficiency of observation and inspection cannot be determined numerically, and the fact that because there was oversight and supervision, the laborers knew exactly what task to work on, how to resolve certain issues, and, for newcomers, how to complete that task. Figure 15 to show the fluctuation in wages paid or owner costs on a daily basis.

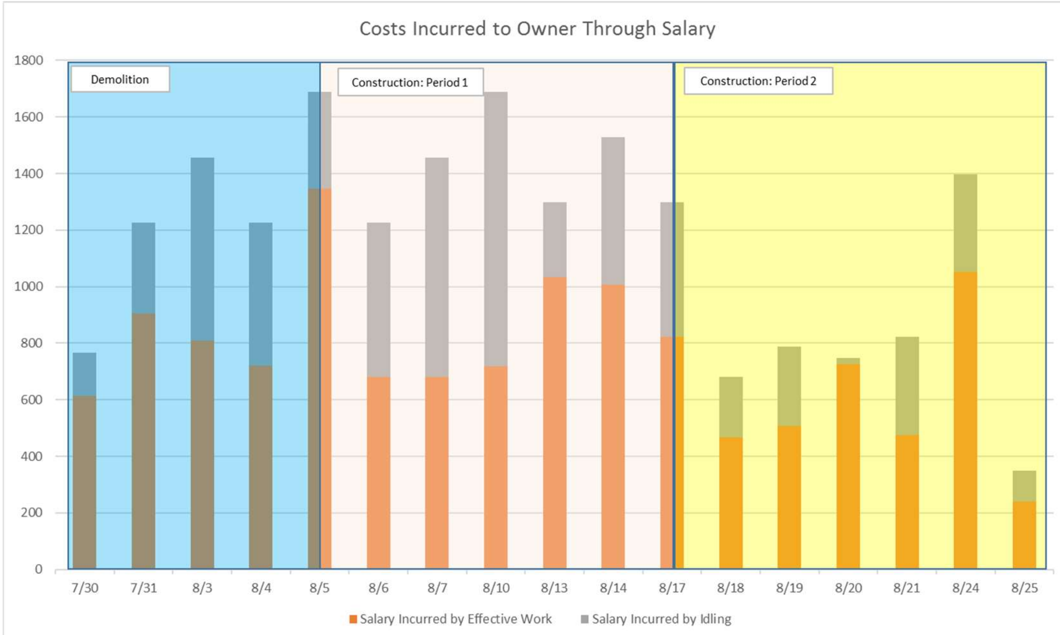


Figure 15: Total Duration (in Worker-hours) Including Effective Work and Idling

On a daily basis, the wages fluctuated based on the hours worked and the number of workers on the field, completing an array of tasks throughout each stage of the case-study. Thus, the cost of $19,645.16 represents the cost that was paid by the contactor to its workers; however, the following wages can be broken down to see what the contractor was paying for in terms of work and idling. Being that the data was collected for each worker, doing each individual task and the efficiency of the worker (whether he was resting or effectively providing towards the completion of the task and for how long), the cost incurred to the owner due to inefficiency can also be calculated. The durations incurred through sub-contracted work i.e. the header concrete saw-cutting, and pouring of the concrete by the concrete truck will not be included in this aspect of the study for two reasons.

1. Concrete saw cutting of the headers occurred before the crew arrived on site

2. Pouring of the concrete occurred concurrently with the shoveling, and vibrating of said concrete (thus, the duration of such a task is already accounted for through other tasks happening simultaneously).

The effective amount of hours to complete a task is determined for future simulation purposes. The inventory of all demolition, cleaning and construction rates are provided in hours. The effective work durations by worker-type on a daily basis allow calculation of the difference between the total time the workers were on the field and the amount of time spent working versus idling (Table 18). Though the costs of subcontracted work are not included in the analysis, when subcontracted work occurred, oversight by a worker representing the prime contractor was necessary; thus, the only financial impact due to the subcontractors that are considered in the analysis is due to wages spent for oversight during subcontracted tasks.

Table 18: Daily worker hours and costs by worker type

Day	Supervision (foreman)	Foreman	Labor	Carpentry	Skidder	Subcontractor	Welding	Effective Work Hours	Idling Hours	Wages - Effective Work ($)	Wages - Idling ($)
1	7	0	9.45	0	0	0.80	0	17.25	3.75	$613.99	$150.20
2	7	1.63	13.8	0	4.48	0.00	0	25.28	9.72	$905.58	$320.75
3	7	0	15.38	0	0	0.00	0	22.38	19.62	$809.85	$647.55
4	7	0.67	12.72	0	0	0.00	0	19.72	15.28	$721.83	$504.50
5	7	0.48	31.68	0	0	0.00	0	38.68	10.32	$1,347.92	$340.55
6	7	0.53	9.77	0	1.68	0.00	0	18.45	16.55	$680.01	$546.32
7	7	0.2	10.45	0	1.03	0.00	0	18.48	23.52	$681.11	$776.29
10	7	0	12.4	0	0.2	0.00	0	19.6	29.4	$717.98	$970.49
13	12.47	0	13	0	0	0.00	1.53	27	8	$1,033.23	$264.08
14	7	0	14.32	5.37	0	0.00	0	26.68	15.32	$1,006.21	$522.17
17	7	0	9.7	4.62	0	0.57	0	21.88	13.12	$821.46	$475.85
18	7	0	4.5	0	0.5	0.00	0	12	6.5	$467.10	$214.60
19	4.5	0	9.03	0	0.42	0.22	0	14.17	8.33	$506.12	$282.24
20	5.25	0	15.1	0	0	0.00	0	20.35	0.65	$724.99	$21.46
21	7	0	3.8	0	1.43	0.33	0	12.57	10.18	$474.80	$347.16
24	9	0	19.77	0	0.33	0.00	0	29.1	10.5	$1,051.85	$346.61
25	2.3	0	1.83	1.83	0	0.00	0	5.97	3.23	$238.87	$111.46
Totals	117.52	3.51	206.7	11.82	10.07	1.92	1.53	349.56	203.99	$12,802.90	$6,842.28

The following data has been provided in Appendix D.1,

- The total number of workers on the field, and the corresponding wages on a daily basis,
- The efficiency measurements based on billable hours during phase 1, and the total durations and efficiency per worker-type.
- Total hours of effective work and idling.
- Wage costs incurred through idling and effective work and efficiency determined through monetary values, daily.
- Total wage costs incurred per worker-type, idling and the efficiency of worker-types based on monetary values.

4.2.2 Fuel Costs

In order to determine the type, amount, and cost of fuel used on the site, all sources of energy were considered. The major sources of energy use are listed in Table 19.

Table 19: On-Field Power Sources' Specs Relating to Fuel Consumption

Power Source	Brand	Model	Fuel-Type	Operating Rate (gallons/hr)	Idling Rate (gallons/hr)
Electric Power Generator	Honda	EB 5000 X	Gasoline	.77	.55
Portable Air Compressor	Airman	PDS 185S	Diesel	1.23-2.31	.8
Skid Steer Loader	Bobcat	S650	Diesel	1.5-2.4	.4
Power Driven Welder	Miller	Big Blue 400 Pro	Diesel	.65	Not Applicable

4.2.2.1 Fuel Consumption

To determine the total amount of fuel consumed by the power sources listed in Table 19, the fuel rates for idling and non-idling work must be established and applied to the corresponding idling and non-idling durations associated with each task. The rates for each power source was determined differently.

4.2.2.1.1 Electric Generator Fuel Consumption

The rates for each power source was determined differently. For the electric power generator, a fuel gauge was visible and data was logged each day. The data logs were comparable enough so that the fuel consumption per hour of usage of the generator was determined for non-idling and idling durations. The electric generator was usually turned on as operations started in the morning, and left on through the day and usually turned off during the lunch break; thus, the total operating time was determinable by logging the few start and stop times throughout each day. The known amount of fuel consumed was calculated when the electric generator was operating and idling (Table 20) with a known tank size of 6.2 gallons.

Table 20: Electric Generator's Effective, and Idling Operating Times and Fuel Consumption, Totals

Total Operating Time (Hr)	54.15
Total Effective Operating Time (Hour)	33.93
Total Idling Time (Hour)	20.22
Percent Operating Time (%)	62.67%
Total Fuel Consumption (Gal)	37.25

Fuel Consumption - Operating (Gal)	26.13
Fuel Consumption - Idling (Gal)	11.12
Fuel Usage Efficiency (%)	78.56 %
% Fuel for Demo.	0 %
% of Fuel for Cg.	11.63 %
% of Fuel for Const.	58.51 %
% of Fuel for Idling.	29.85 %

4.2.2.1.2 Air Compressor Fuel Consumption

A fuel gauge was also available on the air compressor; however, the machinery had mechanical issues making the readings unreliable. A log of the motor's frequency of rotation, in rotations per minute (Rpm), however, were logged for all tasks and compared throughout the duration of the phase for consistency. For determining the environmental impacts, the RPM's were allocated to each of the seven tasks the airman was used for and is recreated in Table 21.

Table 21: Rpm's Logged from the Air Compressor for Each of its 7 Allocations

Arrangement	Reading	Units
1. Idling	1200.00	Rpm
2. One Breaker	1680.00	Rpm
3. Two Breakers	2102.00	Rpm
4. Three Breakers	2550.00	Rpm
5. Airblasting	2813.00	Rpm
6. Sandblasting	2900.00	Rpm
7. Applying Silicone (AT1200S)	1275.00	Rpm

To relate the rpms to the fuel consumption technical data, guidance and assumptions were gathered from the specifications made online, previously referred to in the environmental costing section of the methods chapter, and from a service department technical representative from MMD Equipment (the distributor and owner of the air compressor). The specifications for the Airman PDS 185S-6E1, provides a relationship for between the load experienced by the generator to the rpm's produced ("Airman PDS185S-6E1 Air Compressor | MMD Equipment," n.d.). Three load to fuel consumption relationships were provided in the specification for

- 0% Load: .8 gallons per hour
- 70% Load: 1.7 gallons per hour
- 100% Load: 2.4 gallons per hour

A relationship between low idling and high idling, based was also given in the specifications as

- Low Idle= 1350 rpm
- High Idle= 3000 rpm

The relationship between the frequency of rotation to the loading percentage is provided in Figure 16.

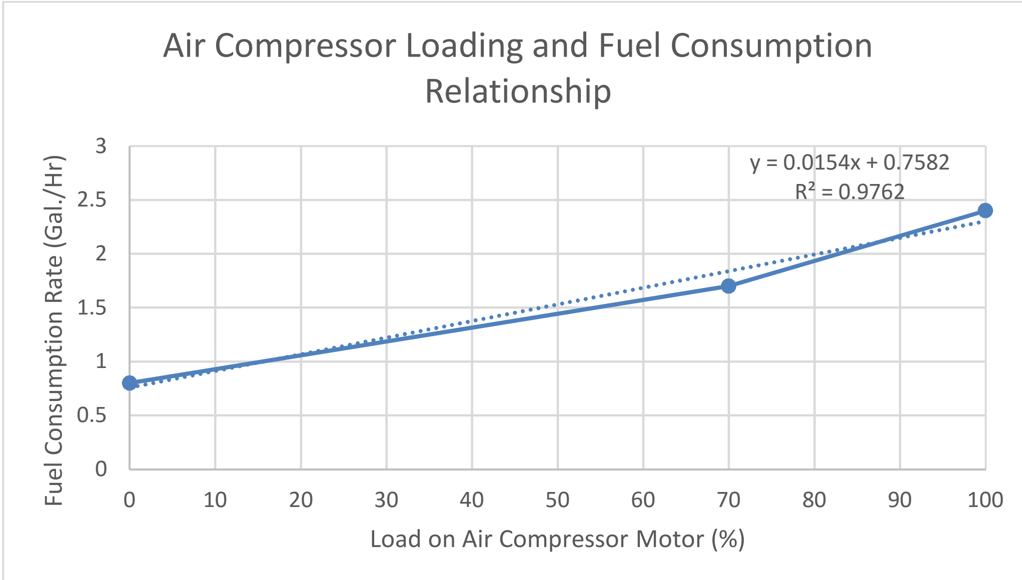


Figure 16: Graphical, and Numerical Expression of Loading on Air Compressor to Fuel Consumption Rate

As can be seen, the relationship is quite linear. Table 22 relates the fuel consumption in gallons per hour for each of the seven allocations of the tasks which are dependent on the air compressor as a power source.

Table 22: Allocated Tasks' Fuel Consumption Rates

Air Compressor Allocation	Frequency of Rotation of Motor (rpm)	Fuel Consumption (Gal/Hr)
1. Idling	1200.00	0.80
2. One Breaker	1680.00	1.23
3. Two Breakers	2102.00	1.60
4. Three Breakers	2550.00	2.00
5. Airblasting	2813.00	2.23
6. Sandblasting	2900.00	2.31
7. Applying epoxy (AT1200S)	1275.00	0.87

Table 23 provides the total operating times (both effective and idling), throughout the case-study, and the resultant fuel consumptions. The last four rows in Table 23, provides the amount of fuel contributed towards idling and the demolition, cleaning, and construction stages.

Table 23: Allocated Tasks Dependent on Air Compressor Fuel Consumption During Effective Work and Idling, Totals

Total Operating Time (Hr)	37.85
Total Effective Operating Time (Hour)	23.50
Total Idling Time (Hour)	14.35
Percent Operating Time (%)	62.09 %
Total Fuel Consumption (Gal)	53.56
Fuel Consumption - Operating (Gal)	42.07
Fuel Consumption - Idling (Gal)	11.48
Fuel Usage Efficiency (%)	78.56 %
% Fuel for Demo.	57.00 %
% of Fuel for Cg.	21.31 %
% of Fuel for Const.	0.24 %
% of Fuel for Idling.	21.44 %

The amount of time spent efficiently working (per allocation) and idling, on a daily basis, and the subsequent fuel consumptions have been tabulated in Appendix D.2.

4.2.2.1.3 Skidder Fuel Consumption

Like the electric generator, the air compressor was left on for an extended number of hours per day. Activities associated with the skidder were as follows

- Breaking, Construction and Cleaning
  - Breaking
  - Driving

- Lifting
- Idling

For such activities, fuel consumption rates were not made available through the specifications online. To determine the fuel consumption rates of such activities the operator of the skidder was asked to read out the fuel consumption that was displayed through the in-cabin monitor, on multiple occasions for each activity. The fuel consumption rate values were logged during the demolition, cleaning and construction stages and are tabulated in Table 24.

Table 24: Fuel Consumption Rates of Skidder's Actions/ Stages

Action/Stage	Fuel Consumption Rate (Gal/Hr)
Idling	0.4
Driving/Cg.	1.5
Lifting/Const.	2
Breaking/Demo.	2.4

Table 25 provides the total operating times (both effective and idling), throughout case-study, and the resultant fuel consumptions. The last column in Table 20, provides a total skidder efficiency usage value in terms of fuel consumption.

Table 25: Idling and Effective (per Allocation) Durations and Effective and Idling Fuel Consumption for Skidder, Totals

Total Operating Time (Hr)	14.32
Total Effective Operating Time (Hour)	10.08
Total Idling Time (Hour)	4.23
Percent Operating Time (%)	70.43 %
Total Fuel Consumption (Gal)	21.14
Fuel Consumption - Operating (Gal)	19.44

Fuel Consumption - Idling (Gal)	1.69
Fuel Usage Efficiency (%)	91.99 %
% Fuel for Demo.	50.91 %
% of Fuel for Cg.	35.72 %
% of Fuel for Const.	5.36 %
% of Fuel for Idling.	8.01 %

The amount of time spent efficiently working (per allocation) and idling, on a daily basis, and the subsequent fuel consumptions have been tabulated in Appendix D.2.

4.2.2.1.4 Power Driven Welder Fuel Consumption

The power driven welder, operator arrived on the site with the sole purpose of welding the sheet metal formwork and the armoring. The power driven welder was operating with an efficiency of 100%, as seen in Table 61. The operator of the power driven welder expressed that the power provided by the unit was a continuous 150 amperes. Though a fuel gauge was available on the unit, a change in the readings were not determinable; thus, the rates provided by the manufacturer's specifications were utilized. It was determined that the fuel consumption rate was .65 gallons per hour ("Big Blue® 400 Pro Engine-Driven Welder | Miller - MillerWelds," n.d.).

The amount of time spent efficiently working and idling, on a daily basis, and the subsequent fuel consumptions have been tabulated in Appendix D.2.

4.2.2.1.5 Total Fuel Consumption

Table 26 provides the durations and fuel consumptions of all of the power sources on the field. The total durations and fuel consumptions are also broken down per power source, work efficiency and the stage.

Table 26: Total Durations and Fuel Consumptions of Effective Work and Idling for all Stage and Power Sources

	Total		Skidder		Air Compressor		Electric Generator		Power Driven Welder	
	Duration (Hours)	%	Duration (Hours)	%	Duration (Worker-hours)	%	Duration (Hours)	%	Duration (Worker-hours)	%
Total	107.85		14.32		37.85		54.15		1.53	
Effective	69.05	63.51 %	10.08	70.43 %	23.5	62.09 %	33.93	62.67 %	1.53	100 %
Idling	38.8	36.49 %	4.23	29.57 %	14.35	37.91 %	20.22	37.33 %	0	0 %
Demo.	22.78	21.43 %	4.48	31.32 %	18.3	48.35 %	0	0 %	0	0 %
Const.	32.84	29.45 %	0.57	3.96 %	0.15	0.4 %	30.59	56.5 %	1.53	100 %
Cg.	13.42	12.63 %	5.03	35.16 %	5.05	13.34 %	3.34	6.17 %	0	0 %
	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%
Total	112.94		21.14		53.56		37.25		1	
Effective	88.64	78.3	19.44	91.99	42.07	78.56	26.13	70.15 %	1	100 %
Idling	24.29	21.7	1.69	8.01	11.48	21.44	11.12	29.85	0	0
Demo.	41.29	36.88	10.76	50.91	30.53	57	0	0	0	0
Const.	25.05	21.49	1.13	5.36	0.13	0.24	22.79	61.18	1	100
Cg.	22.3	19.93	7.55	35.72	11.41	21.31	3.34	8.97	0	0

4.2.2.1.6 Fuel Consumption Costs

To determine the cost of all of the fuel used (112.95 gallons of diesel and gasoline), the U.S. Energy Information Administration (EIA) was referred to for the representative dates (Table 27) ("Gasoline and Diesel Fuel Update - Energy Information Administration," n.d.).

Table 27: Cost Rates per Gallon of Gas and Diesel Utilized

Average East Cost of Gasoline per Gallon	2.47
Average East Cost of Diesel per Gallon	2.71

Thus, with the durations of power source fuel usages for idling and effective work, the known fuel type of each power source, and the costing rate, the total costs can be determined as are provided in Table 28. Thus, the total fuel cost is therefore **$296.94** of which 21.27% was incurred through idling equating to $63.15.

Table 28: Total Fuel Consumptions and Fuel Costs of Effective Work and Idling for Stage 1 and of all Stage and Power Sources

	Total		Skidder		Air Compressor		Electric Generator		Power Driven Welder	
	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%	Fuel Consumption (Gal)	%
Total	112.94		21.14		53.56		37.25		1	
Effective	88.64	78.3 %	19.44	91.99 %	42.07	78.56 %	26.13	70.15 %	1	100 %
Idling	24.29	21.7 %	1.69	8.01 %	11.48	21.44 %	11.12	29.85 %	0	0 %
Demo.	41.29	36.88 %	10.76	50.91 %	30.53	57 %	0	0 %	0	0 %
Const.	25.05	21.49 %	1.13	5.36 %	0.13	0.24 %	22.79	61.18 %	1	100 %
Cg.	22.3	19.93 %	7.55	35.72 %	11.41	21.31 %	3.34	8.97 %	0	0 %
	Fuel Cost ($)	%	Fuel Cost ($)	%	Fuel Cost ($)	%	Fuel Cost ($)	%	Fuel Cost ($)	%
Total	$296.94		$57.20		$144.93		$92.10		$2.70	
Effective	$233.79	78.73 %	$52.62	91.99 %	$113.86	78.56 %	$64.61	70.15 %	$2.70	100 %
Idling	$63.15	21.27 %	$4.58	8.01 %	$31.07	21.44 %	$27.49	29.85 %	$0.00	0 %
Demo.	$111.74	37.63 %	$29.12	50.91 %	$82.62	57 %	$0.00	0 %	$0.00	0 %
Const.	$62.47	21.04 %	$3.07	5.36 %	$0.35	0.24 %	$56.35	61.18 %	$2.70	100 %
Cg.	$59.58	20.07 %	$20.43	35.72 %	$30.89	21.31 %	$8.26	8.97 %	$0.00	0 %

4.2.3 Material Costs

The materials applied within the demolition stage were the gases used by the torching/ heat cutting tasks which utilized two tanks of dissolved acetylene and compressed oxygen contained in 145 and 228 ft^3 tanks; the ratio each of these gasses used were, according to foreman, roughly 1:1. Thus, acetylene would run out of gas first and the foreman would refill both tanks. It was assumed that both tanks would run out of gas at the same time since they would both be refilled at the same time. The only expenditures incurred to the contractor during the cleaning stage for material uses were the abrasives used during the sandblasting treatment; otherwise all costs incurred were due to wages and fuel use. All consumable materials, other than fuel, were used during the two periods within the construction stage. All material usage amounts, usage rates, costs, and resources from which the total material costs have been determined throughout the demolition, construction, and cleaning stages have been tabulated and provided in Appendix D.3 with commentary.

The total costs of all materials used throughout all stages of the phase was **$18,090.43.** Table 29 provides the total costs per material-type utilized in the field.

Table 29: Total Costs and Relevancy

Costing Designation	Cost	% of Total
Pre- Demolition	$7,660.13	42.34 %
Steel Reinforcement	$1,090.31	6.03 %
Adhesives for Steel Reinforcement	$141.52	0.78 %
Formwork Material	$426.34	2.36 %
Concrete and Related Materials	$600.58	3.32 %
Armoring System and Extrusion	$7,730.28	42.73 %
Silicone and Methacrylate	$262.42	1.45 %
Cleaning and Demolition	$178.86	0.99 %
Total Material Cost	$18,090.43	100%

As can be seen in Table 29, the majority of the material costs incurred to the owner were through the pre-demolition and the armoring system and extrusion material costs, together providing 85.07% of the total material costs, or $15,390.40. The third most expensive cost was the steel reinforcement at $1,090.31, 6.03% of the total material costs.

4.2.4 Total Owner Costs

The total owner cost was determined by summing the wage, fuel and material costs. The total costs incurred to the owner are provided in Table 30.

Table 30: Total Costs and Relevancy

	Costs ($)	% of Total
Wages	$19,645.17	51.90 %
Fuel Consumption	$112.94	0.30 %
Material Consumption	$18,090.43	47.80 %
Total Owner Costs	**$37,848.53**	

As can be seen in Table 30, the majority of the costs incurred to the owner are through wages and material consumption, together forming 99.70% of the costs, or $37,753.59. The costs of wages and material consumption, of $19,645.17 and $18,090.43, respectively, were quite close in value. As previously shown the idling fuel cost was 21.27% of the total fuel cost. Worker idling hours cost $6,842.25, or 18.08% of the total costs incurred to the owner. Though such a value would concern the owner, it should be noted that compared to other crews the one laboring on Edgemoor Road, was quite efficient, according to the inspector that was on the site on a daily basis. Also, such a value is reflective of nearly every moment that the worker was not effectively working, it should be understood that time lost to idling cannot be eliminated and is necessary for the worker to carry on throughout the day.

4.3 Societal Costs of Case Study

The societal costs, or the delay and vehicle operating costs incurred to user, is dependent on the duration at which the work-zone is present as well as the number of vehicles and freight trucks affected during that time. The work-zone on the Edgemoor bridge necessitated that the eastbound direction of traffic take a detour. At the same time 2 of the 3 lanes of the westbound direction closed. The increase in travel time for the westbound direction was considered inconsequential and not enough to cause motorists to take the detour. The westbound direction was considered to experience the same traffic volume as during normal operation but a drop in speed due to the increase in congestion.

4.3.1 Road-User Database

The acquisition of traffic data before, during, and after construction on the bridge is of the upmost importance in determining the societal costs. The collection of traffic data in the state of Delaware is done so in compliance with DelDOT. Specifically, DelDOT utilizes its Traffic Monitoring System (TMS) while using The Traffic Data System (TRADAS) software to retrieve traffic related data. The ADT, though determined from the NBI data, must also be established for both of the opposing directions of traffic. To determine the number of average daily users traversing the bridge in the east and westbound direction, Traffic Pattern Groups (TPGs), attained from the Delaware Vehicle Volume Summary Book of 2014, must be employed. Each TPG represents a group of roadways with similar traffic characteristics in a similar manner to that of the FHWA's functional classes. DelDOT has developed 8 TPG's that represents the following FHWA functional classes (*Delaware Vehicle Volume Summary 2014 (Traffic Summary)*, n.d.),

TPG 1- Interstate, Freeways and Expressways

TPG 2- Other Urban Arterials

TPG 3- Urban Collectors

TPG 4- Urban Local Streets

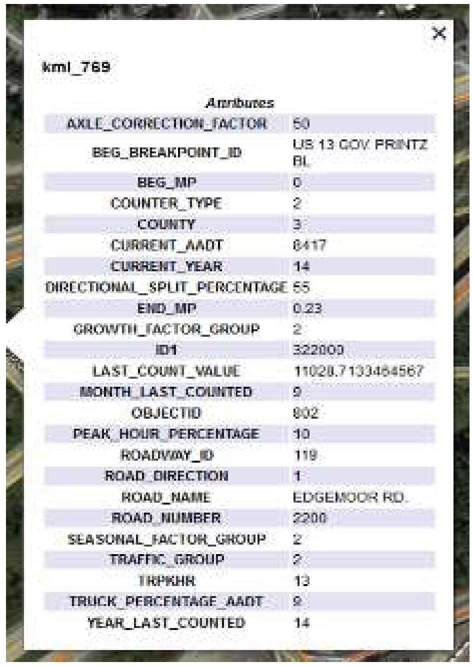
TPG 5- Rural Arterials

TPG 6- Rural Major Collectors

TPG 7- Rural Minor Collectors and Local Roads

TPG 8- Recreational Routes

Edgemoor Road over Amtrak, according to FHWA's NBI is an urban collector, which would lead one to assume that the bridge falls under TPG 3. However, according to the Google Earth KMZ file, which DelDOT has imbedded with geospatial data regarding specific roadways, Edgemoor Road is considered to fall under TPG 2 (or "Other Urban Arterials"). The imbedded data gathered for Edgemoor Road can be seen in Figure 17. Thus, DelDOT data was utilized with the assumption that the roadway to fall under TPG 2.



kml_769

Attributes	
AXLE_CORRECTION_FACTOR	50
BEG_BREAKPOINT_ID	US 13 GOV PRINTZ BL
BEG_MP	0
COUNTER_TYPE	2
COUNTY	3
CURRENT_AADT	8417
CURRENT_YEAR	14
DIRECTIONAL_SPLIT_PERCENTAGE	55
END_MP	0.23
GROWTH_FACTOR_GROUP	2
ID1	322000
LAST_COUNT_VALUE	11028.7133464567
MONTH_LAST_COUNTED	9
OBJECTID	802
PEAK_HOUR_PERCENTAGE	10
ROADWAY_ID	119
ROAD_DIRECTION	1
ROAD_NAME	EDGEMOOR RD.
ROAD_NUMBER	2200
SEASONAL_FACTOR_GROUP	2
TRAFFIC_GROUP	2
TRPKHR	13
TRUCK_PERCENTAGE_AADT	9
YEAR_LAST_COUNTED	14

Figure 17: 2014 ATR Data for Edgemoor Road (https://www.deldot.gov/information/pubs_forms/manuals/traffic_counts/2014/2014ATRlocations.kmz)

It should be noted that the values utilized in this study would be considered design values that were determined to be representative of the actual traffic conditions on the structure. Only when traffic data is calculated with the utilization of site-specific volume and signal and stopping delay data (in both directions) before and after the presence of the work-zone, will the data calculated be considered completely accurate. Uninterrupted flow is only considered in this study. The vehicle operating and passenger delay costs presented throughout this document are conservative estimates as they do not include signal delay and the increase in congestion of the detour routes due to lane closures of Edgemoor Road.

For phase 1, the following durations and total amount of vehicles and trucks traversing the structure in the presence of a work-zone and on the detour were calculated and provided in Table 31.

Table 31: Total Vehicles, Traversing Structure and Detours, per Month and Day Type

Month	July	August
Total Duration	Duration: Days	Duration: Days
	2.0	25.0
Weekdays	Duration: Weekdays	Duration: Weekdays
	2.0	17.0
Weekends	Duration: Weekends	Duration: Weekends
	0.0	8.0
Automobiles: Weekdays	Total Automobiles on Detour: Weekdays	Total Automobiles on Detour: Weekdays
	7176.1	61394.1
	Total Automobiles on Structure: Weekdays	Total Automobiles on Structure: Weekdays
	8770.8	75037.3
Automobiles: Weekends	Total Automobiles on Detour: Weekends	Total Automobiles on Detour: Weekends
	0.0	28882.7
	Total Automobiles on Structure: Weekends	Total Automobiles on Structure: Weekends
	0.0	35301.1
Trucks: Weekdays	Total Trucks on Detour: Weekdays	Total Trucks on Detour: Weekdays
	709.7	6071.9
	Total Trucks on Structure Weekdays	Total Trucks on Structure Weekdays
	867.4	7421.3
Trucks: Weekends	Total Trucks on Detour: Weekends	Total Trucks on Detour: Weekends
	0.0	2856.5
	Total Trucks on Structure: Weekends	Total Trucks on Structure: Weekends
	0.0	3491.3

The strategies and data utilized in determining the vehicular volume for the case-study, in both directions, have been provided in Appendix E.3.

4.3.2 Effects of Structural Dimensions and Associated Speeds

Before calculating the passenger delay and vehicle operating costs on the structure and detour, the length and travel speeds of the detour links must be determined as shown in Table 32. The detour links included travel from US Highway 13 to 12th Street and then onto a ramp.

Table 32: Detour Speeds and Distances and Incurred Additional Traveling Distance and Duration per Vehicle

Component	Speed Limits (mph)	Detour Traveled (miles)	Duration per Vehicle (hour)
US13	35.00	2.00	0.06
12th Street	25.00	0.90	0.04
Ramp (from 12th)	25.00	0.20	0.01
Totals	-	3.10	0.10

Since the effect of detouring vehicles on the bypasses are not considered in thus study, the speed limits on the detour links are considered to be constant and equal to the posted speed. For vehicles using the detour, the increase in distance traveled will affect the costs incurred to the driver and passengers in terms of delay time and vehicle operating distance and speed. The travel delay time and vehicle operating costs incurred to motorists traversing the structure with the presence of a work zone, however, is determined on an hourly basis.

Thus, in the presence of a work-zone the following speeds in Table 33 are assumed,

Table 33: Designated Speeds on Edgemoor Road, with Work-Zone, Westbound Direction During Weekdays and Weekends

Hour	Weekday Speeds (mph)		Weekend Speeds (mph)	
	Eastbound	Westbound	Eastbound	Westbound
0	-	17.5	-	17.5
1	-	17.5	-	17.5
2	-	17.5	-	17.5
3	-	17.5	-	17.5
4	-	17.5	-	17.5
5	-	17.5	-	17.5
6	-	17.5	-	17.5
7	-	15.75	-	17.5
8	-	15.75	-	17.5
9	-	17.5	-	17.5
10	-	17.5	-	17.5
11	-	15.75	-	17.5
12	-	17.5	-	17.5
13	-	15.75	-	17.5
14	-	17.5	-	17.5
15	-	12.25	-	17.5
16	-	14	-	17.5
17	-	14	-	17.5
18	-	15.75	-	17.5
19	-	17.5	-	17.5
20	-	17.5	-	17.5
21	-	17.5	-	17.5
22	-	17.5	-	17.5
23	-	17.5	-	17.5
(https://www.google.com/maps/@39.752409,-75.5038284,213m/data=!3m1!1e3!5m1!1e1)				

The strategies and data utilized in determining the vehicular speed on the structure before and during the work-zone have been provided in Appendix E.4.

Before calculating the work zone user delay costs, it was necessary to determine the distribution of automobile and trucks on the detours and structure on an hourly basis on weekdays and weekends during both phases.

4.3.3 Traveler Delay Time and Costs

The detour delay time (DDT) and travel delay time (TDT) measure the amount of extra time incurred to motorists and passengers due to the presence of a work-zone. The number of passengers and drivers must be determined to scale the lost time by considering the AVO. Freight trucks are considered to have an AVO of 1; whereas passenger vehicles are considered to have an AVO of 1.67 representing all purposes for travel (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011). 8,417 Vehicles traversed the Edgemoor bridge per day. 9% of the vehicles traversing the structure are trucks, the remaining 81% are passenger vehicles. 55% of vehicles travel in the primary direction, westbound, across the structure.

4.3.4 Vehicle Operating and Road User Delay Costs

DelDOT has provided factors developed to reflect the monetary value of time for motorists, organized by the type of vehicle being driven ("Design Guidance Memorandum Road User Cost Analysis," 2015), as shown in Table 34.

Table 34: DelDOT, 2015 Value of Time

Vehicle Type	Cost ($/Hr)
Auto	19.77
Light Trucks	19.55
Heavy Trucks	29.14

With the vehicle operating cost constants provided by DelDOT, it initially seems that the vehicle operating factors can be implemented with the information provided and calculated thus far in this section, that is until it is recognized that the speeds determined during normal and work-zone conditions, during both phases, do not discretely coordinate with the costing parameters provided below. Thus, based on the values made available by DelDOT ("Design Guidance Memorandum Road User Cost Analysis," 2015) in Table 35, the intermediary values were correlated in Appendix E.5 and used in the analysis.

Table 35: DelDOT, 2015 Vehicle Operating Cost

Speed (mph)	Autos ($/Mile)	Trucks ($/Mile)
15	0.45	1.00
25	0.43	0.86
35	0.42	0.80
45	0.41	0.77
55	0.41	0.75
65	0.40	0.73

Now that the following have been determined,

- Hourly volume of automobiles and trucks during normal conditions on weekdays and weekends in both directions
- Hourly volume of automobiles and trucks during work-zone conditions on weekdays and weekends in both directions
- Speed of all vehicles during normal conditions on weekdays and weekends in both directions
- Speed of all vehicles on detours and detour component distances
- Speed of vehicles and volume of vehicle types traversing the westbound direction, on a weekday and weekend basis, during the case-study road user value of time
- Average vehicle occupancy
- Vehicle operating costs

The total road user costs can now be determined, by first determining the total road user cost incurred to drivers and passengers during normal condition, without the work-zone. Table 36 provides the road user costs without the work-zone, for vehicles traversing the structure in the eastbound and westbound directions.

Table 36: Total Road User Cost with No Work-Zone

Road User Cost	Component	Travel Direction		Total ($)
		Eastbound	Westbound	
Vehicle Operating Costs ($)	On-Structure	$2,825.41	$3,383.41	$6,208.81
	On-Detour	$0.00	$0.00	$0.00
Passenger Delay Costs ($)	On-Structure	$6,043.64	$6,311.62	$12,355.26
	On-Detour	$0.00	$0.00	$0.00
Total Road User Costs ($)			$18,564.07	

As seen in Table 36, road users in the eastbound direction incur less cost than those in the westbound direction and are 45.51% and 54.49% of the total vehicle operating cost without the work-zone, respectively. Note that the vehicle operating costs incurred to the users in both directions is similar to the directional split value provided by DelDOT. The passenger delay costs, however, are higher in the eastbound direction than the westbound direction and are 48.92% and 51.08% of the total passenger delay costs, respectively. The passenger delay costs were higher for the eastbound direction, despite less volume on a daily basis, due to the congestion and resulting speed decrease in that direction. The total costs incurred to road users during normal traffic conditions within the time range of the case-study is $18,564.07; though this value will not be considered as an incurred cost to the road users, it will be used to reduce the costs incurred due to the work-zone so as not double count vehicle operating and passenger delay costs. The total vehicle operating cost and passenger delay cost were 33.45% and 66.55% of the total costs incurred to road users during normal traffic conditions within the time range of the case-study.

The total vehicle operating and road user delay costs incurred can be seen in Table 37.

Table 37: Total Road User Cost Due to Work-Zone

Road User Cost	Component	Travel Direction		Total ($)
		Eastbound	Westbound	
Vehicle Operating Costs ($)	On-Structure	$0.00	$3,806.38	$3,806.38
	On-Detour	$174,965.54	$0.00	$174,965.54
Passenger Delay Costs ($)	On-Structure	$0.00	$12,925.53	$12,925.53
	On-Detour	$343,349.36	$0.00	$343,349.36
Total Road User Costs ($)			$535,046.81	

As seen Table 37, vehicle operating costs, for users traversing the structure, were not incurred in the westbound direction as that direction was completely diverted to the detour. Passenger delay costs, for users assumed to traverse a particular detour, were not incurred on the eastbound direction of the structure. It was assumed that, due to the short length of the bridge, the increase in congestion due to the work-zone would not deter the users from using the bridge as the extended duration to traverse the structure would still be more attractive than traversing the 4.4-mile detour route that the travelers in the eastbound direction would have to take. Similar to the proportions calculated for the normal traffic conditions within the time range of the case-study, the vehicle operating cost and passenger delay cost were 33.41% and 66.59% of the total road user costs incurred due to the work-zone of $535,046.81.

As previously mentioned, the vehicle operating and passenger delay costs incurred during the work-zone do not accurately depict the total road user cost as it does not deduct the road user costs under normal conditions, incurred to the road users regardless of the work-zone. Table 38 provides the net road user cost and the reflective impact of the work-zone on users of Edgemoor Road during demolition, cleaning and construction of the case-study.

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Table 38: Net Road User Cost Due to Work-Zone

Road User Cost	Component	Travel Direction		Total ($)
		Eastbound	Westbound	
Vehicle Operating Costs ($)	On-Structure	$0.00	$422.97	$422.97
	On-Detour	$172,140.13	$0.00	$172,140.13
Passenger Delay Costs ($)	On-Structure	$0.00	$6,613.91	$6,613.91
	On-Detour	$337,305.72	$0.00	$337,305.72
Total Road User Costs ($)			$516,482.74	

The net value of the total road user costs is $528,552.03. Similar to the road user costs under normal and work-zone conditions, vehicle operating costs and passenger delay costs were consisted of 33.41% and 66.59% of the total road user cost of $516,482.74. Thus, it seems that the incurred user delay costs and vehicle operating costs increased proportionally from the incurred costs they costed users if no work-zone were present. The costs incurred to users traversing the structure in the presence of the work-zone (in the westbound direction) only experienced 1.36% of the total road user costs while the users traversing the detours experienced 98.64% of the total cost; thus, overwhelmingly, the costs incurred to the users were mostly due to detour delay costs and detour operating costs for automobiles and trucks

4.4 Environmental Costs of Case Study

The environmental costs consider the impacts from energy used during joint replacement operations and from increases in emissions from vehicles using the detour. This section will determine the amount of emissions produced by each power source used in the field and cost them. This section will also provide the increase in emissions from vehicles traversing the work zone and detours, and cost them in the same manner as the power sources.

4.4.1 In-Field Power Sources Environmental Impact

The duration at which each power source was utilized effectively and when idling be converted into emitted pollutants. The pollutants considered are shown in Table 39. Durations spent effectively and idling were converted to emitted pollutants by utilizing MOVES. In the MOVES software, the emission factor for equipment, such as the air compressor, is determined by the equipment type (power sources), horse-power, fuel type, location (New Castle County), date, and time of day (corresponding to the case-study dates and work-hours).

Based on the horsepower the proper emission factors can be determined from MOVES. The pollutant types considered from the MOVES' software output for each power source were those that had known costs. The costing factors come from the most recent emission cost estimates provided by Caltrans published in the 2012, which is based on Californian geography. The costing factors were taken from the "L.A./South Coast($/ton)" column due to the fact Edgemoor Road was also in an similarly urban location near the coast. A costing factor was not given to PM2.5; thus, the HERS-ST EEA tool, was used to determine the proportion of PM10 to PM2.5 costing factors. From the HERST-ST EEA tool tabulated results, it was determined that the PM10 and PM2.5 emission cost factors were equal. Thus, PM 2.5 was provided with the same costing factor as PM 10.

Table 39: Emitted Pollutants Considered for Costing Purposes

Emitted Pollutants
Atmospheric CO2
Carbon Monoxide (CO)
Fine Particulate Matter (PM 2.5)
Oxides of Nitrogen (NOx)
Road Dust (PM 10)
Sulfur Dioxide(SO2)
Volatile Organic Compounds (VOC)

The amount of emitted pollutants for each power source by multiplying the emission factors by the duration at which each power source was used effectively and when idling. The total emissions for the electric generator are shown in Table 40.

Table 40: Total Emissions for Each Power Source

Emitted Pollutants	Emitted Pollutants of Power Sources (tons)				Total Emissions per Pollutant (tons)
	Electric Generator	Air Compressor	Skidder	Power Driven Welder	
Atmospheric CO2	5.51E-01	1.09E+00	6.30E-01	4.39E-02	2.31E+00
Carbon Monoxide (CO)	1.45E-01	2.01E-03	5.40E-03	3.86E-04	1.53E-01
Fine Particulate Matter (PM 2.5)	5.46E-05	3.25E-04	7.92E-04	5.19E-05	1.22E-03
Oxides of Nitrogen (NOx)	1.18E-03	7.49E-03	5.02E-03	3.61E-04	1.40E-02
Road Dust (PM 10)	5.93E-05	3.35E-04	8.16E-04	5.35E-05	1.26E-03
Sulfur Dioxide(SO2)	1.00E-05	6.50E-06	4.07E-06	2.96E-07	2.09E-05
Volatile Organic Compounds (VOC)	2.34E-03	4.66E-04	1.13E-03	9.43E-05	4.04E-03

After determining the total pollutants emitted, determined in grams from the MOVES software, costing factors must be utilized. The costing factors will convert the total pollutants to costs using Table 41.

Table 41: Costing Factors Utilized with Mass of Pollutants Emitted

Emitted Pollutant	$/Ton
Atmospheric CO2	$23.00
Carbon Monoxide (CO)	$75.00
Fine Particulate Matter (PM 2.5)	$139,900.00
Oxides of Nitrogen (NOx)	$12,900.00
Road Dust (PM 10)	$139,900.00
Sulfur Dioxide(SO2)	$69,800.00
Volatile Organic Compounds (VOC)	$1,210.00

The following have been determined to calculate environmental costs of the joint replacement at the Edgemoor Road bridge,

- The total duration of operation and idling from all power sources,
- The emission factors for and total mass of emitted pollutants from each power source, and
- The costing factors of emissions.

With the list above determined, the total costs can now be calculated the case-study. Table 42 provides the total costs, due to effective and idling processes, per power source and the total environmental cost.

Table 42: Total Environmental Costs Due to Power Sources

Emitted Pollutants	Emitted Pollutant Costs ($)		Total Cost ($)
	Idling	Effective	
Electric Generator	$21.72	$36.45	$58.17
Air Compressor	$81.58	$133.60	$215.19
Skid Steer Loader	$90.55	$215.68	$306.23
Engine Driven Welder	$0.00	$20.58	$20.58
Total Idling Cost		$193.85	
Total Effective Cost		$406.31	
Total Cost		$600.17	

Thus, the total environmental cost of the power sources was $600.17. 32.30%, or $193.85, of the total cost were the costs incurred through idling of the power sources while 67.70%, or $406.31, of the total environmental impact of the in-field power sources' environmental impacts.

4.4.2 Vehicular Environmental Impact

Determining the pollutant costs associated with vehicles traversing the structure and detours due to the presence of the work-zone were calculated in a similar fashion as the vehicle operating costs. Emission factors from the 2003 static emission EMFAC model, developed by the California Air Resource Board (CARB), referred to as "Vehicular Emissions", were used. The vehicle emissions by weight are determined by vehicle traveling speed and the distance traveled.

The total incurred environmental costs due to vehicles during the case-study is the difference in emissions between normal operations and during the work zone. The total environmental impact of the vehicular emissions is provided in Table 43. The mass and subsequent costs of the emitted pollutants from vehicles both traversing the structure and detours, during normal operations and during the work-zone, are provided in Appendix F.

Table 43: Total Incurred Environmental Costs of Vehicles

Emitted Pollutants	Pollutant Costs Emitted from Vehicles per Direction ($)		Total Emitted Pollutant Costs ($)
	Eastbound	Westbound	
Carbon Monoxide (CO)	$249.25	$0.19	$249.44
Oxides of Nitrogen (NOx)	$10,637.20	$45.62	$10,682.82
Road Dust (PM 10)	$3,230.46	$29.15	$3,259.61
Oxides of Sodium (Sox)	$329.92	$4.61	$334.52
Volatile Organic Compounds (VOC)	$383.27	$3.12	$386.38
Total Costs	$14,830.10	$82.67	$14,912.77

Thus the total environmental impact of the vehicles traversing the structure (in the westbound direction) and those traversing the detours (eastbound direction) equates to $14,912.77. The westbound direction only provided $82.67 of the total environmental impact due to speed changes of the constant volume before and during the existence of the work-zone. The rest of the $14,830.10 was incurred due to vehicles detouring on a route that had a distance that was 60 times longer than that of the structure's length, and consisted of lower speeds.

Thus, the total environmental cost, including the on-site power sources and extra vehicle travel due to the work zone, was $15,512.94, of which 3.87% of the total cost was due to the on-site power sources, and 96.13% of which was due to the vehicular emissions.

4.4.3 Total Costs of Case Study

The total cost is the sum of the owner, user, and environmental costs. The general subdivisions of the cost categories are provided in Table 44.

Table 44: Total Cost per Costing Category and per Costing Component

Costing Category	Costing Components	Components' Costs	**Total Cost of Category**	Percentage of Total
Owner Costs	Wage Costs	$19,645.17	**$38,032.53**	6.67 %
	Fuel Costs	$296.94		
	Material Costs	$18,090.43		
Road User Costs	Vehicle Operating Cost	$172,563.10	**$516,482.74**	90.61 %
	Road User Cost	$343,919.64		
Environmental Costs	On-Site Power Source Env. Cost	$600.17	**$15,512.94**	2.72 %
	Vehicular Env. Cost	$14,912.77		
Total Cost		**$570,028.21**		

Thus, the total costs incurred through the owner, society (road users) and the environment totals to $570,028.21, of which 6.67% of the cost is due to the owner costs, 90.61% is due to the road user costs, and 2.72% is due to the environmental costs. Note that though the road user costs are quite high. These values are still conservative as calculations for the structure and the detours associated with the work zone were done so by assuming uninterrupted flow. Signal delay times, shockwaves, and decelerating and accelerating of the vehicles all contribute to the total road user and environmental costs but were neglected in this study. Costs incurred by idling of either workers and/or equipment in terms of wages, fuel, and the environmental impact summed to $7,099.26. of which 96.38% of it went towards wages, .89% towards fuel and 2.73% towards environmental impact. The total costs incurred through idling was therefore 1.25% of the total cost. A breakdown of the costing categories can be seen in Figure 18 and the breakdown of the costing components can be seen in Figure 19.

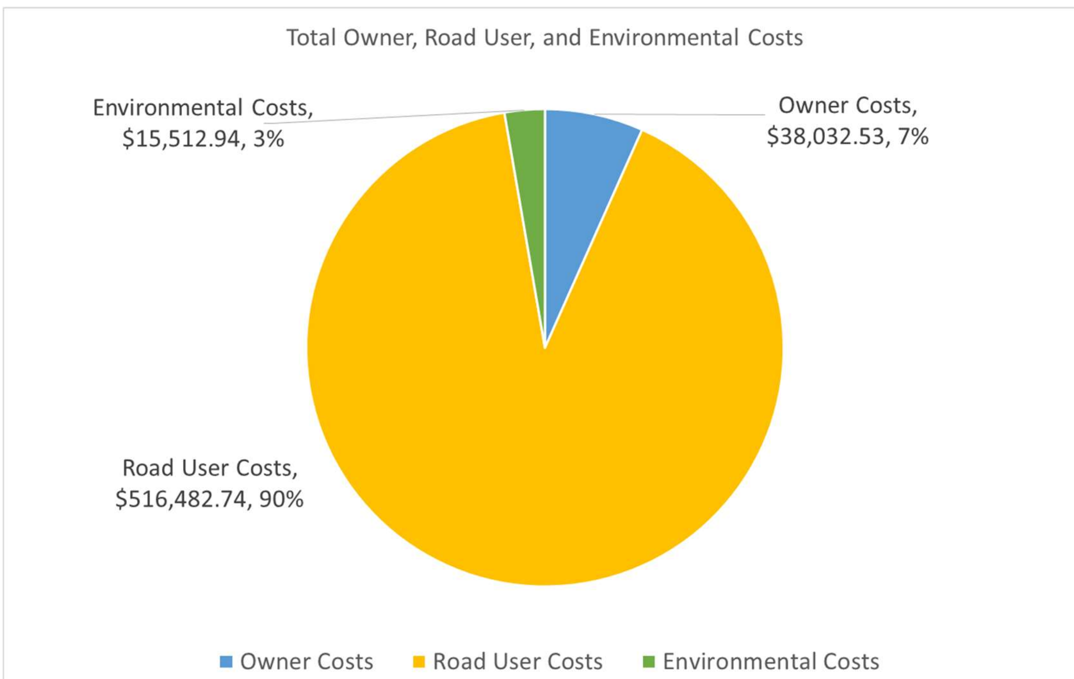


Figure 18: Total Costs Depiction per Costing Category

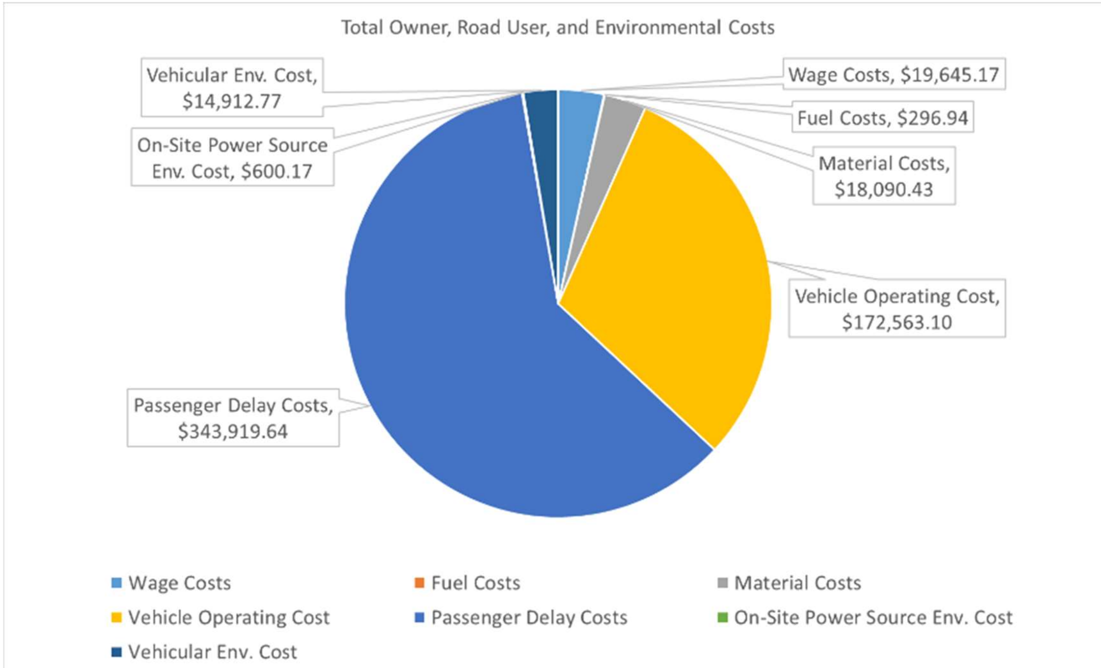


Figure 19: Breakdown of Costing Categories into its Components

4.5 Simulated and Optimized Cost of Case Study

The maintenance of a joint and its adjacent headers can involve the combination of full and partial depth removals and replacements of the headers and the replacement of the sealants of the join systems. Utilizing the durations, rates, and costs associated with the completion of the tasks necessitated in providing the full depth replacement of the headers and sealants of Edgemoor Road, Section 4.2 will re-simulate and optimize the durations and costs associated with the following tasks

- Partial depth removal of the backwall, deck, and total dam with Class A concrete
- Partial depth removal of the backwall, deck, and total dam with elastomeric concrete
- Full depth removal of the dam with Class A concrete
- Sealant removal and placement with

- Closed Cell Foam Compression Seal (CCF)
- Open Cell Compression Seal (OCS)
- V-Seal (VS)
- Strip Seal (SS)

After the optimized durations and costs associated with each task are determined for each header and sealant-type replacement mentioned above, the life expectancies will be determined for said activities. With the durations, costs, and longevity associated with each activity mentioned above, and the remaining years left of the bridge's design life, an optimized joint maintenance schedule for the bridge's remaining years of assumed serviceability. Before re-simulating and optimizing the actions studied on the field, adjustment must be made to some of the observations witnessed.

Some of the costs that will be provided in this section have been rescaled, using the demolition, construction, material and fuel usage, road user impact, and emission impact rates, so that such values can be more relatable to common obstacles faced by decision makers. For example, if the dimensions of the headers were abnormally large, meaning that on Edgemoor Road the dimensions cut out for the headers were larger than what an engineer would usually request, all durations and associated costs would be rescaled to determine the holistic impact the new cut-out dimensions, to reduce the presence of anomalies witnessed during the case study so that the rates and values determined are more applicable to other studies. If changing the dimensions of the aforesaid headers, for example, would not hypothetically be possible by a contractor were he or she working on the same structure as the case-study, or would not contribute positively to the overall costs, such a value would not be rescaled. An explanation of what values were modified, why they were modified and by what magnitude is provided in the following paragraphs before the associated costs of the varying partial depth replacement costs are determined.

4.5.1 Partial Depth Simulation

The following section will provide the costs associated with various types of header rehabilitation and replacement actions that an engineer could face when deciding what course of action to take or when scheduling. Specifically, this section will provide the following,

- The holistic costs associated with partial depth replacement
  - Of the backwall and deck headers, independently
  - Of the dam blockout (including the deck and backwall headers)
  - Using Class A concrete
  - Using Elastomeric Concrete

4.5.1.1 **Partial Depth Adjustments for Simulations**

Asphaltic plug joints were considered for implementation; however, after consulting with a DelDOT representatives it was expressed that an APJ would be more useful on roadways that are characterized by a continuous flow of traffic with near constant speeds. Due to the fact that at both abutments of Edgemoor Road, there are intersections and that the road is characterized by an ample amount of stop-and-go vehicular behavior it was decided by the contractor that such as joint should not be applied on the structure. The APJ will therefore not be considered in the simulations.

The blockout is the rectangular portion of the riding suface that surrounds the joints forming the headers. During maintenance and rehabilitation of joints is saw cut then demolished, forming the region within which the rehabilitation and replacement will take place. The blockout forms the edges of the joint and it is where the anchorage and armoring systems are placed within (Purvis, 2003). Regardless of the joint chosen to be rehabilitated or replaced, the treatment incurred to the blockout can be analyzed independently of the joint. If it is decided that the blockout along with the armoring system or joint gland is to be rehabilitated or replaced, according to a number of contractors and maintenance manuals, the headers will be subjected to either partial depth or full depth removal.

According to the NCHRP 319 study, and confirmed by the inspector on Edgemoor Road as well as a company representative that wishes to stay anonymous, who will be referred to as Company A, the bridge deck headers tend to be between 1.5 to 2 feet wide, spanning the length of the joint to be replaced or rehabilitated. It will be assumed that the deck header of the blockout will be 1.5 feet wide. In the case of the backwall of the abutment expansion joint, the width of the header to be removed is restricted by the width of the backwall, of 1 foot. Thus, the backwall width and the 1.5-foot width of the deck header will provide a 2.5-foot wide blockout that consists of Class A concrete.

The joint, between the headers and within the blockout, when subject to rehabilitation or replacement, will be subjected to either partial or full depth removal.

Full depth removal is rare, and is usually employed when the armoring system is to be replaced. Partial depth removal usually occurs when the headers, and not the armoring system, is to be rehabilitated or partially replaced. The replacement of the gland or sealant material between the armoring would be replaced in conjunction with partial or full depth header removal and replacement if said headers necessitate such treatment, otherwise the sealant or gland would be removed or replaced.

The actions taken on the field were juxtaposed with those suggested by the 2015 DelDOT Maintenance Manual, and it was deemed that the in-field actions, including exceptions such as breaking with the skidder, followed those suggested by the manual closely. Procedures regarding partial and full depth removal of unsound concrete will be utilized from the case studies and complimented by the DelDOT 2012 Maintenance Manual. According to the DelDOT maintenance manual, partial depth repair of concrete headers must first be cut with a concrete saw (to a minimum depth of 1 inch, but not deep enough where the steel reinforcement is cut), the unsound concrete must be broken with thirty pound pneumatic breakers, and the amount of concrete demolished must be to a minimum depth of the top layer of steel reinforcement (Taavoni & Tice, 2012). After demolition is complete, the voided area must be subjected to sandblasting and airblasting to clear it of foreign particles so that the new concrete may bond properly to the steel reinforcement and in-place concrete. As can be seen, the armoring system and anchorage, and all steel reinforcement were kept intact on the northern abutment back wall and only supplemented by a row of rebar, shown in Figure 20. A few of the operations shadowed during the case study period included a deck patching operation; Figure 21 depicts another project where partial depth removal of concrete was provided and where demolition and excavation provided a depth of uncovered concrete up to the upper steel reinforcement layer.

Figure 20: Shallow Depth Removal of North Abutment Backwall Expansion Joint, with Partial Deck Patching in the Surrounding Area

Figure 21: A deck Patching Operation that Provided a Shallow Depth Concrete Replacement to the Upper Steel Reinforcement Mat

The depth associated with partial depth removal of concrete varies from site to site being that the depth demolished is dependent on how loose the concrete is while it is being demolished. Once the concrete seems sturdy, and the loos concrete above it has been excavated, the depth of the demolition is then finalized. Though such a value varies from site to site and is based on subjective assessments, it was deemed that many of the partial depth removal tasks, that were similar in approach, also exhibited similar depths of concrete that was demolished and excavated. As previously mentioned, a partial depth replacement took place on the northern abutment expansion joint, backwall in which the armoring was left in place and the backwall concrete was removed. The depth to which the backwall of the north abutment was demolished will be considered the partial depth removal depth associated with Edgemoor Road.

The depth of the backwall demolished of the northern abutment expansion joint was 7.5" deep, or .625 feet, 4.75 inches shorter than the depth exhibited by the backwall demolished by the southern abutment expansion joint. It is assumed that the backwall and deck header demolition depth, will be equal to one another, as they were in the full depth demolition exhibited southern abutment joint. Table 45 provides the dimensions associated with the partial depth removal of backwall and deck headers.

Table 45: Adjusted Backwall and Deck Header Geometries for Partial Depth Replacement Simulations

Dimension	Backwall Header	Deck Header
Depth (ft)	.625	.625
Width (ft)	1	1.5
Length (ft)	39.41	39.41
Volume (ft^3)	24.63	36.95

4.5.1.2 **Partial Depth Effective and Expected Durations**

Referring to Table 69, in Appendix A.2, the total duration, in worker-hours, provided on the site during the second and third day of the case study, for laborers tasked with breaking, took a total of 58 worker-hours. A partial depth replacement of the concrete headers would consist of a demolition rate of 1.98 ft^3/WHr of effective work, as determined from the case study; thus the effective duration to remove the backwall is 12.43 worker-hours and the total effective duration to partially remove the deck is 18.65 worker-hours. With an idling efficiency of 41.67% associated with the laborers tasked with breaking, the expected duration to partially remove the backwall and deck headers is 17.61 and 26.42 worker-hours, respectively, totaling 44.04 worker-hours of expected breaking labor. It is expected that the duration to partially remove the backwall and deck headers would take 2 days in total, and if only one side of the dam were subjected to a partial depth removal, it would only take one day to complete said task, regardless of the side. The partially removed headers would be subjected to intermittent airblasting and a final sandblasting treatment, before the new concrete would be poured and treated. As is the case on the majority of partial depth replacements witnessed during the case studies, the steel reinforcement for partial depth replacements will be considered not to have been replaced. Also observed, was the fact that any concrete saw cutting intended to cut the perimeter of the blockout, was done so before the crew arrived, will not be included in the simulation. Table 46 provides the tasks and durations associated with the partial depth removal of the backwall, deck, and total dam of the template structure's southern abutment expansions joint; the backwall and deck headers are considered independently due to the fact that partial depth replacement of headers is not always subjected to both sides of the dam.

Table 46: Effective and Expected Durations Associated with Backwall, Deck, and Total Dam Partial Depth Replacement

Stage	Index	Task	Tool	Applicant	Component's Element	Index Dependencies	Backwall Eff.Drtn. (WHr)	Deck Eff.Drtn.(WHr)	Backwall Exp.Drtn (WHr)	Deck Exp.Drtn (WHr)
Demo.	1	Concrete Sawing	Handheld Saw	-	Concrete	-	-	-	-	-
Demo.	2	Breaking	TPB	-	Concrete	1(C)	12.43	18.65	17.61	26.42
Cg.	3	Airblasting	Airblaster	-	Debris	-	0.36	0.54	0.36	0.54
Cg.	4	Sandblasting	Sandblaster	-	Rubble	3(C)	0.15	0.22	0.15	0.22
Const.	5	Placing	By Hand	Cork	Formwork	4(C)	1.67	-	2.48	-
Const.	6	Spraying	By Hand	Concrete Adhesive	-	5(C)	0.03	0.07	0.03	0.07
Const.	7	Pouring	Concrete Truck	Wet Concrete	-	6(C)	0.12	0.18	0.12	0.18
Const.	8	Shoveling	By Hand	Wet Concrete	-	6(C)	0.24	0.36	0.24	0.36
Const.	9	Vibrating	Vibrator	-	Wet Concrete	8(C)	0.12	0.18	0.12	0.18
Const.	10	Smoothing	By Hand	-	Wet Concrete	9(C)	0.80	2.00	1.03	2.58
Const.	11	Spraying	By Hand	Curing Compound	Wet Concrete	10(C)	0.02	0.05	0.02	0.05
Const.	12	Placing	By Hand	Burlap	Wet Concrete	11(C)	0.27	0.27	0.27	0.27
Const.	13	Placing	By Hand	Weeper Hose	Wet Concrete	12(C)	0.07	0.07	0.07	0.07
Const.	14	Placing	By Hand	Tarp	Wet Concrete	13(C)	0.07	0.07	0.07	0.07
Const.	15	Curing of Concrete	-	-	Concrete	14(C)	72.00	72.00	72.00	72.00
Const.	16	Grinding	Grinder	Cork	Formwork	15(C)	0.20	-	0.30	-
Const.	17	Applying	By Hand	Primer	Cork	16(C)	0.05	-	0.05	-
Const.	18	Pouring	AT 1200 S	Silicone	Interface with Approach	17(C)	0.15	-	0.15	-
Const.	19	Curing of Silicone	-	-	Backwall	18(C)	0.42	-	0.42	-

Const.	20	Applying	By Hand	Methacrylate	Poured Silicone	19(C)	0.08	-	0.08	-
Const.	21	Curing of Methacrylate	-	-	Backwall	20(C)	6.00	-	6.00	-
Cg.	22	Smoothing	Grinder	Conrete	Dam	21(C)	0.45	1.13	0.67	1.68

As can be seen in Table 46, the curing duration of the poured concrete is provided as its own task. Curing was not considered as a task in previous calculations because enough time will have gone by for the concrete to completely cure. According to the New Jersey Department of Transportation Standard Specifications for Road and Bridge Construction of 2007, the curing applications to the newly poured concrete (i.e. the wet burlap, weeper hose, and plastic tarp shown in Table 46) must be applied for no less than 3 days ("Standard Specification for Road and Bridge Construction," 2007), which the contractor abided to in the case study. The curing time for the silicone, poured between the backwall and approach interface, also requires a curing time and is considered its own task as does the methacrylate applied between the new silicone seal and the approach shown in Table 46. The curing time, or tack-free time, for the two-part silicone application and the methacrylate is .42 and 6 hours, respectively, before traffic can drive over the backwall. Thus, the silicone and methacrylate applications should be provided while the concrete is nearing the end of its curing period. The total expected durations, in worker-hours, to complete a partial depth replacement of the backwall, deck, and both headers (the dam) is provided in Table 47.

Table 47: Total Expected Duration of Associated Backwall, Deck, and Total Dam Partial Depth Replacement per Stage

Total Durations Expected (WHr)			
Stage/Task	Backwall	Deck	Dam
Demolition	17.61	26.42	44.04
Curing	78.42	72.00	78.42
Construction	4.45	3.83	8.28
Cleaning	1.18	2.45	3.63
Total Expected Duration (WHr)	101.67	104.70	134.37

4.5.1.3 **Partial Depth Work Schedule and Total Costs**

The number of workers, and daily schedule must be determined. The material costs and the cost of emitted pollutants of the power sources are not dependent on the tentative schedule that was developed; however, the costs incurred through wages, road user costs, and the environmental costs of vehicles change by the total number of days the work-zone is up. Before determining the costs incurred to the owner, society, and environment, the daily schedule of the partial depth removal of the backwall, deck, and dam must be produced. Table 48 provides the expected schedule and durations to complete the tasks associated with the partial depth removal and replacement of Class A concrete on the backwall side of the header. Included in the duration is the time necessary for the concrete to wet-cure and the tack-free time of the silicone and methacrylate to completely cure. It is recommended that no workers be on the site during the wet curing of the concrete and the curing of the methacrylate (a total duration of 78 hours), unless other operations on the structure are occurring concurrently so that such workers can be used effectively. It is also recommended, as shown in the simulation, that work begins on the portion of the abutment with the newly poured concrete immediately after the 72 hour curing duration for the concrete, regardless of the time of day. The start and end designations determine the time of the day that the task would start and when it would end, dependent on the number of workers providing that service. The times are presented in the 24-hour, decimal format. Being that the tasks are generally sequential and dependent on one another, it is assumed that those involved with a task in the beginning of that day, would complete their task and then move on to the next one. Thus, the workers present at the beginning of each new day, providing service for a specific task, would be reutilized with each subsequent task, of which the number of participants from the preceding task(s) would be designated. With more than 3 breakers in the backwall and deck header demolition, it is assumed that more than one air compressor would be available to be delivered to the site, otherwise the number of workers and rates would need to be re-utilized to provide a new schedule. The schedule presented provides the optimum number of workers to complete the partial demolition and replacement of the headers without finishing early in the day so that wages are not wasted on time not spent working; it is assumed that each worker would have an agreed upon duration for which that worker would get salary for that day. Also, the schedule presented for the backwall and deck header partial removal are constructed so that if a partial replacement of the dam were necessary, the two groups, one on each side of the dam, can work as concurrently as possible. For some of the tasks, the increase in the number of workers speeds up the completion of work, for other tasks, too many workers may get in one another's way and reduce efficiency.

Table 48: The Simulated Schedule Associated with the Partial Depth Removal and Replacement of the Backwall and Deck Headers

Stage	Index	Workers on Backwall	Backwall			Workers on Deck	Deck		
			Start Time	End Time	Day		Start Time	End Time	Day
Demo.	2	4	7.50	11.90	1	6	7.50	11.90	1
Cg.	3	1	12.90	13.26	1	1	12.90	13.44	1
Cg.	4	1	13.26	13.41	1	1	13.44	13.67	1
Const.	5	2	13.41	14.65	1	-	-	-	-
Const.	6	1	14.65	14.68	1	1	13.67	13.74	1
Const.	7	-	-	-	-	-	-	-	-
Const.	8	1	14.68	14.92	1	1	13.74	14.10	1
Const.	9	1	14.68	14.80	1	1	14.10	14.28	1
Const.	10	3	14.92	15.27	1	3	14.28	15.14	1
Const.	11	1	15.27	15.28	1	1	15.14	15.19	1
Const.	12	1	15.28	15.35	1	1	15.19	15.25	1
Const.	13	1	15.35	15.42	1	1	15.25	15.32	1
Const.	14	1	15.42	15.49	1	1	15.32	15.39	1

Const.	15	-	15.49(1)	15.49(3)	3	-	15.39(1)	15.39(3)	3
Const.	16	1	15.49	15.79	3	-	-	-	-
Const.	17	1	15.79	15.84	3	-	-	-	-
Const.	18	1	15.84	15.99	3	-	-	-	-
Const.	19	-	15.99	16.41	3	-	-	-	-
Const.	20	1	16.41	16.49	3	-	-	-	-
Const.	21	-	16.49	22.49	3	-	-	-	-
Cg.	22	2	23.49	23.83	3	2	15.39	16.23	3

Thus, for the backwall header, it has been determined that a total of 4 laborers, with the presence of the foreman, would be able to begin and complete the demolition, and construction stage up to the beginning of the curing time. The total owner, societal (road user), and environmental costs for partial replacement of the backwall header is shown in Table 49.

Table 49: Backwall Header Partial Replacement Total Cost: Total Owner, Road User, and Environmental Cost

Costing Category	Costing Components	Components' Costs	**Total Cost of Category**	Percentage of Total
Owner Costs	Wage Costs	$1,292.50	**$2,579.18**	4.20 %
	Fuel Costs	$35.12		
	Material Costs	$1,251.55		
Road User Costs	Vehicle Operating Cost	$19,099.86	**$57,164.13**	93.03 %
	Passenger Delay Costs	$38,064.27		
Environmental Costs	On-Site Power Source Env. Cost	$54.60	**$1,705.28**	2.78 %
	Vehicular Env. Cost	$1,650.67		
Total Cost		**$61,448.58**		

For the deck header, 6 workers are necessary on the first day to begin and complete the demolition stage and the construction stage up to the time where the concrete must cure. The schedule above includes the range of activities that were observed during the case-study which includes the time from the initiation of demolition to when construction activities were completed and the second phase began; thus. the time saved by the proposed schedule above would consist of 3 days, which does not include the duration for the concrete to fully cure, only to wet- cure. The partial replacement of the deck header is provided in Table 50.

Table 50: Deck Header Partial Replacement, Total Cost per Costing Parameter

Costing Category	Costing Components	Components' Costs	**Total Cost of Category**	Percentage of Total
Owner Costs	Wage Costs	$1,679.22	**$2,746.55**	5.34 %
	Fuel Costs	$43.45		
	Material Costs	$1,023.88		
Road User Costs	Vehicle Operating Cost	$15,778.37	**$47,230.01**	91.89 %
	Passenger Delay Costs	$31,451.64		
Environmental Costs	On-Site Power Source Env. Cost	$56.31	**$1,420.23**	2.76 %
	Vehicular Env. Cost	$1,363.92		
Total Cost		**$51,396.78**		

It is assumed that once one crew is finished with its side of the dam, it will leave the field and arrive immediately after the 72-hour wet curing process of the concrete. Thus, being that the partial deck and backwall removal simulations were calculated separately, all costs, except for those incurred vehicles (road user or environmental costs), are summed together. The total costs incurred by the vehicles are dependent on which side takes the longest duration to be completed; thus the side with the longest duration will define the duration of time of expected lane closure, and that side's vehicle operating, passenger delay, and environmental costs will define the road user costs and one of the two components of the environmental costs. All results for the simulation of the partial dam removal is provided in Table 51.

Table 51: Partial Dam Replacement, Total Cost: Total Owner, Road User, and Environmental Cost

Costing Category	Costing Components	Components' Costs	**Total Cost of Category**	Percentage of Total
Owner Costs	Wage Costs	$2,971.72	**$5,325.73**	8.29 %
	Fuel Costs	$78.58		
	Material Costs	$2,275.44		
Road User Costs	Vehicle Operating Cost	$19,099.86	**$57,164.13**	88.97 %
	Passenger Delay Costs	$38,064.27		
Environmental Costs	On-Site Power Source Env. Cost	$110.91	**$1,761.58**	2.74 %
	Vehicular Env. Cost	$1,650.67		
Total Cost			**$64,251.44**	

Note that the total cost of the partial dam removal varies by $2,802.86, from the total cost of the partial backwall removal. The relatively low difference in costs, compared to the magnitude of the differing operations, is due to the fact that the road user costs, in most of the simulations provided in this study (as well as the case-study), are between 80 to 95% of the total costs.

Many of the operations shadowed during the case-study, not including Edgemoore Road, were tasked with utilizing elastomeric concrete instead of Class A concrete. Elastomeric concrete was used due to the fast curing duration compared to that of Class A concrete. The material and applicative costs of the elastomeric concrete was assumed to be similar to the material costs of the Class A concrete through on-field observations and discussions with various contractors. The contractors are fully cognizant that elastomeric concrete provides a shorter life expectancy than Class A concrete, but they are often required to utilize such admixtures due to time constraints imposed by the DOT on certain roadways. Edgemoore Road did not utilize the elastomeric concrete due to the fact that there were no time constraints on the project and other operations were occurring on the field simultaneously, allowing for extra time to allow the stronger, Class A, concrete to cure.

Elastomeric concrete will not be considered as a possible substitute for Class A concrete, due to the face that, based on the feedback of the inspectors and contractors during the case studies, because of their short life expectancies. Elastomeric concrete will only be considered as a substitute for Class A concrete during partial depth replacements. Thus, the simulated costs to implement a partial depth removal of the entire dam, with elastomeric concrete, is shown in Table 52. Thus, through the use of elastomeric concrete, the only costs affected are the road user costs and the environmental costs, specifically the vehicular environmental costs due to detouring vehicles and congestion as a result of lane closures.

Table 52: Deck and Backwall Header Partial Replacement with Elastomeric Concrete Total Cost: Total Owner, Road User, and Environmental Cost

Costing Category	Costing Components	Components' Costs	Total Cost of Category	Percentage of Total
Owner Costs	Wage Costs	$1,292.50	**$2,579.18**	11.62 %
	Fuel Costs	$35.12		
	Material Costs	$1,251.55		
Road User Costs	Vehicle Operating Cost	$6,353.65	**$19,021.41**	85.66 %
	Passenger Delay Costs	$12,667.75		
Environmental Costs	On-Site Power Source Env. Cost	$54.60	**$603.99**	2.72 %
	Vehicular Env. Cost	$549.38		
Total Cost		**$22,204.57**		

The replacement of the sealant, in between the armoring, may be subject to removal and replacement depending on the assessment of the sealant. As previously mentioned, the sealants subject to simulations are the strip seal, open cell compression seal, closed cell foam seal, and V-Seal. The durations and all associated holistic costs associated with replacing the previous seal and implementing one of the four new seals above would be added to end of the curing of the methacrylate, or the end time of index 21, of Table 48, if a partial depth removal of the headers is also necessitated. Likewise, the costs relevant to each sealant type would also be added after the appropriate curing and tack-free durations associated with the full depth removal times.

The sealant replacement schedule is dependent on the header replacement schedule. If a header is subjected to a full depth replacement, then the sealant will be subjected to a newly constructed sealant replacement. As aforementioned, the sealant life expectancies are dependent on whether the sealant is newly constructed (upon the replacement of the armoring) or if they are replaced without the replacement of the armoring. A discussion of the associated sealant replacement costs, independent of the actions incurred by the headers, will be discussed before simulations over the remaining life of the bridge is provided to determine the most optimal joint maintenance program for Edgemoor Road.

4.5.2 Sealant Replacement Simulation.

In the following section, the sealants chosen to be simulated will be done so by isolating the act of implementing a sealant between the armoring, and costing the subsequent monetary impacts the isolated tasks. Along with the diurnal simulations, the life expectancy of each sealant type, and the material costs associated with each sealant, will be and juxtaposed.

4.5.2.1 **Applicable Sealants to Case-Study**

Before providing the simulation results associated with the different sealant types, the sealants that are applicable to the Edgemoor Road must be determined. Specifically, the range of expansion and contraction of the southern abutment expansion joint must be taken into account. The range of motion of the expansion joint was determined from the Superintendent Book, where temperature (in degrees, Fahrenheit) were correlated with the expected dimension of the dam and is provided in Table 53.

Table 53: Temperature to Reservoir Dimension

Temp. (F)	Dim. (in)
110	1.53
100	1.64
90	1.76
80	1.87
70	1.98
60	2.09
50	2.2
40	2.31
30	2.42
20	2.53
10	2.65
0	2.76
-10	2.87

Thus, the maximum displacement of the southern expansion joint is 2.87 inches. All sealants provided in the simulation will be those that accommodate 3 inches of movement and can be adhered to steel armoring. The sealants considered in the study are the

- Closed Cell Foam Compression Seal (CCF)
- Open Cell Compression Seal (OCS)

- V-Seal (VS)
- Strip Seal (SS)

4.5.2.2 **Sealant Work Schedule and Total Costs**

The duration of implementing the seal, and subsequently the duration of the Phase, will differ based on the type of seal chosen. 4 workers will be necessary to complete the seal removal and implementation, 1 of which is the foreman, 2 of which are laborers, and 1 of which is the carpenter, regardless of the sealant chosen. It is recommended that 4 of the workers be kept from the fourth shift or that the workers laboring under Phase 2 supplement the 4 workers of the fourth shift at a later time, to reduce overhead for the owner.

If a strip seal is implemented between the armoring, the duration to implement the seal will be 3.64 hours or 3 hours and 38 minute. Table 54 provides the implementation of the strip seal between the armoring and the final airblasting treatment. The strip seal once implemented into the armoring, though an adhesive is used, can incur traffic as soon as it is implemented. Being that the start time for implementing a seal varies from the header(s) rehabilitated, and the magnitude at which said component(s) are rehabilitated or replaced, the sealant replacement will be simulated to begin and endure during the time of day with the most traffic on Edgemoor Road in the month of August, during a week day, so as to provide conservative road user cost and road user environmental impact results.

Table 54: Strip Seal Implementation and Airblasting Duration

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)
Const.	22	Placing	By Hand	SS	Armoring	Dam	57(C)	10.92	3.00	3.64
Cg.	23	Airblasting	Airblaster	-	Debris	All	58(C)	1.02	1.00	1.02

Table 55 provides the implementation of the OCS between the armoring and the final airblasting treatment. A backer rod is not required underneath the seals between the armoring and the seal can adhere to either concrete or steel. According to a D.S. Brown representative, with an appropriate crew, the compression seal and V-seal should take about 30 minutes to implement according to the dimensions of the roadway subjected to the case-study. However, the adhesive used for the compression seals is the DSB 1520, which requires a 2-hour drying period ("Delastic Preformed Compression Seals," n.d.)

before traffic is allowed to drive over it. Table 55 depicts the duration of implementing the compression seal. Thus, the duration from implementing the seal to the end of its curing duration is 2.5 hours or 2 hours and 30 minutes.

Table 55: Open Compression Seal Implementation and Airblasting Duration

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)
Const.	22	Placing	By Hand	OCS	Armoring	Dam	57(C)	0.50	3.00	0.50
Cg.	23	Airblasting	Airblaster	-	Debris	All	58(C)	1.02	1.00	1.02
Crng.	24	Curing of Adhesive	-	-	Wet Adhesive	-	60(C)	2.00	-	2.00

The V-Seal utilizes a high strength, 2-part, epoxy adhesive specifically developed for the V-Seal known as the "V-Epoxy-R Epoxy Adhesive" that necessitates between 8 to 10 hours to cure before usage ("V-Seal Expansion Joint Systems | D.S. Brown," n.d.). The CCF is simulated to incur the exact same duration as the VS when implementing and curing. Also, like the CCF, the like expectancy of the V-Seal, according to the D.S. Brown representative, based on his professional experience, is 5 years. Though a life expectancy of the sealant was not provided for maintenance and replacement of the V-Seal, it will be assumed to have the same life expectancy of the CCF of 2 years. Though discontinued by D.S. Brown, the "CEVA" was a CCF sealant manufactured by the company and the old specifications were provided by the D.S.Brown representative. Upon being implemented during new construction, the sealant, when available, was to be adhered to a concrete or steel structure with the use of the "Bonder No.1" adhesive produced by the Chase Corporation; the bonder, like the "V-Epoxy-R Epoxy Adhesive", necessitates between 8 to 10 hours of initial curing. Table 56 depicts the duration of implementing the V-Seal with an assumed 8 hour curing period. Thus, the duration from implementing the seal to the end of its curing duration is 8.5 hours or 8 hours and 30 minutes.

Table 56: V-Seal Implementation and Airblasting Duration

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)
Const.	22	Placing	By Hand	VS and CCF	Armoring	Dam	57(C)	0.50	3.00	0.50
Cg.	23	Airblasting	Airblaster	-	Debris	All	58(C)	1.02	1.00	1.02
Crng.	24	Curing of Adhesive	-	-	Wet Adhesive	-	60(C)	2.00	-	8.00

The time at which the sealants are implement are dependent on the following cases

- Which side of the header will be subject to partial depth removal
- If both sides of the header be subject to partial depth removal
- If the header be subject to full depth removal
- If the joint is to simply be subjected to a sealant replacement without any actions provided to the headers

The time of day during which the sealant replacement occurs will affect the societal and environmental costs due to the fact that both costs are dependent on the number of vehicles traversing the structure and detours, and the manner at which they traverse such structures. Due to the variability of the start times for the sealant replacement actions, the most conservative start times were chosen for each sealant type during the month of August. The duration to implement each sealant type was iteratively applied to each hour, and the total amount of vehicles inconvenienced by each sealant type was determined. The start times that would ultimately inconvenience the least amount of users were chosen. During the case-study, the carpenter was usually responsible for the implementation of the strip seal. The rate of implementing the strip seal is highly dependent on the workers that are providing such a service; the rate at which a strip seal can be implemented varies drastically from an inexperienced laborer to one who is experienced. The carpenter was unavailable for the majority of the strip seal implementation; however, when the carpenter was involved in implementing the sealant, the rate increased dramatically. Thus, the rate at which the strip seal was implemented was changed to reflect the rate at which the carpenter (with the assistance of other laborers) implemented the seal. Table 57 provides the durations, start and end times, and the number of vehicles affected by solely the sealant replacement.

Table 57: Conservative Simulation of Sealant Implementation Start Times Dependent on Duration to Place Sealant and Number of Vehicles Affected, Duration, Time Range

Sealant Type	Duration of Seal Implementation (Hr)	Implementation Start Time	Implementation End Time	Vehicles Affected
SS	3.64	14.00	17.64	2671
OCS	2.50	15.00	17.50	2085
VS and CCF	8.50	10.00	18.50	5331

Upon determining sealants to be considered in simulations, there are two factors that deem said sealants worthy of consideration, regarding an abutment expansion joint such as that of Edgemoor Road. The duration to implement the joint and the life expectancy of the joint will affect owner, environmental, and societal impacts incurred due to the replacement of a previous sealant and the implementation of a new one. The cost per linear foot of the sealant will affect the owner cost only and is inconsequential when juxtaposed to the costs incurred through wages and the road user costs; for example, in the case study, the total cost of the strip seal was $546.17 while the road user cost, for the duration of the case-study, was $516,482.74. Table 58 provides the estimated cost per linear foot of the sealant and any adhesives per linear foot provided by the D.S. Brown representative.

Table 58: Costs of Sealants and Adhesives, Subject to Simulation, per Linear Foot

Sealant	Manufacturer	Product Name	Cost of Seal ($/LF)	Cost of Adhesive ($/LF)	Total Cost of Sealant ($/LF)	Comments
CCF	D.S.Brown	CEVA	6.5	1.1	7.6	Cost of adhesive provided by manufacturer representative

SS	D.S.Brown	Steelflex	15	0.01	15.01	Cost of adhesive calculated by usage amount during case-study and cost per gallon provided by manufacturer sales representative
OCS	D.S.Brown	Delastic	20		20	Cost of adhesive included in cost of seal
VS	D.S.Brown	V-Seal	30		30	Cost of adhesive included in cost of seal

The total owner, road user, and environmental costs associated with each sealant type is provided in Table 59. The influence of each sealants life expectancy upon new construction and rehabilitation is not a factor in Table 59 and will be acknowledged later in the section.

Table 59: Simulated Sealant Replacements' Total Costs per Sealant Type in Ascending Order of Cost

Total Costs per Sealant Type ($)							
OCS				**SS**			
Costing Category	Costing Components	Components' Costs	Total Cost of Category	Costing Category	Costing Components	Components' Costs	Total Cost of Category
Owner Costs	Wage Costs	$154.86	$883.09	Owner Costs	Wage Costs	$554.62	$1,101.16
	Fuel Costs	-			Fuel Costs	-	
	Material Costs	$728.23			Material Costs	$546.54	
Road User Costs	Vehicle Operating Cost	$1,512.11	$4,540.14	Road User Costs	Vehicle Operating Cost	$1,937.17	$5,810.35
	Passenger Delay Costs	$3,028.03			Passenger Delay Costs	$3,873.18	
Environmental Costs	On-Site Power Source Env. Cost	-	$130.90	Environmental Costs	On-Site Power Source Env. Cost	-	$167.61
	Vehicular Env. Cost	$130.90			Vehicular Env. Cost	$167.61	
Total Cost		$5,554.13		Total Cost		$7,079.12	
CCF				**VS**			
Costing Category	Costing Components	Components' Costs	Total Cost of Category	Costing Category	Costing Components	Components' Costs	Total Cost of Category
Owner Costs	Wage Costs	$154.86	$431.59	Owner Costs	Wage Costs	$154.86	$1,247.21
	Fuel Costs	-			Fuel Costs	-	
	Material Costs	$276.73			Material Costs	$1,092.35	
Road User Costs	Vehicle Operating Cost	$4,175.37	$12,505.71	Road User Costs	Vehicle Operating Cost	$4,175.37	$12,505.71
	Passenger Delay Costs	$8,330.34			Passenger Delay Costs	$8,330.34	

Environmental Costs	On-Site Power Source Env. Cost	-	$361.16	Environmental Costs	On-Site Power Source Env. Cost	-	$361.16
	Vehicular Env. Cost	$361.16			Vehicular Env. Cost	$361.16	
Total Cost		$13,298.45		Total Cost		$14,114.07	

As can be seen in Table 59, the most cost efficient seal, again without considering the life expectancy of the sealant type, varies between the materials and their costing components and costing categories. The costing components represent the sub-sections associated with the owner, road user, and environmental costs. The cost of the category refers to the cost of each of the three pillars for each sealant. Table 60 provides the total holistic cost in ascending order from top left to bottom right. The most cost efficient sealant type for each costing component and costing category is provided in Table 60.

Table 60: Sealant Types Associated with the Lowest Costing Component and Category, and the Sealant Associated with the Lowest Overall Cost without Considering Life Expectancy

Costing Category	Costing Components	Sealant with Lowest Associated Cost Component	Sealant with Lowest Associated Cost Category
Owner Costs	Wage Costs	OCS, VS,&CCF	CCF
	Fuel Costs	-	
	Material Costs	CCF	
Road User Costs	Vehicle Operating Cost	OCS	OCS
	Passenger Delay Costs	OCS	
Environmental Costs	On-Site Power Source Env. Cost	-	OCS
	Vehicular Env. Cost	OCS	
Total Lowest Costing Seal		OCS	

Table 61 tabulates the life expectancies of each sealant type per new construction (total replacement) and after rehabilitation of the sealants.

Table 61: Life Expectancy of Each Sealant Type During New Construction and Rehabilitation/Replacement

Sealant	Life Expectancy (Years)	
	New Construction	Replacement/ Rehabilitation
OCS	15	6
CCF	5	2
VS	5	2
SS	15	10

Table 61 has tabulated the life expectancies of the joint, determined through the sources provided in the literature review and based on feedback from manufacturer representatives. It should be noted that the replacing of the armoring, during a full depth replacement, and subsequently the application of a new sealant is considered in the simulations to be a "new construction" endeavor. The replacement of the sealant itself and/or during partial depth removal of the headers is considered to be "replacement/rehabilitation" of the sealant, as in the Milner & Shenton III study. Thus, to properly simulate and forecast an optimized expansion joint sealant schedule, the simulated headers removals (partial or full depth) must initially be optimized.

Though the open cell compression seal does portray comparable life expectancies to the strip seal, many agencies, are phasing them out, due to their inconsistent life expectancy rates and vulnerability to failure for various reasons (Milner & Shenton III, 2014). Due to the fact that the CCF and VS sealants have the highest implementation costs and lowest life expectancies, both for new and rehabilitative construction, it can immediately be inferred that such sealants are inferior to the SS and OCF sealants in every way possible. Due to the total financial impacts of implementing the CCF and VS, and their short life expectancies shown in Table 61, such sealants should never be used, regardless of the remaining life duration of the sealant system for which a sealant must be utilized. Thus in the simulations of the sealants over the lifetime of the bridge, CCF and VS's will not be utilized as they can be ruled out immediately.

4.5.3 Full Depth Simulation

Before determining the simulated schedule, work-crews, and the resultant costs of a full depth removal, minor adjustments must be made to some of the geometric values and practices observed during the case-study so as to make the values provided more applicable to other project. As previously mentioned, the full depth removal is not a common rehabilitation technique when providing joint maintenance or rehabilitation. The primary intent when providing a full depth removal is to provide new, uncompromised, concrete and gain access to the anchorage system of the armoring, remove it, and replace it. Based on observations during the case-study, opinions given by Company A and the inspector from Edgemoor Road, the following observations and points were made

- The armoring is embedded into the parapet. Though the parapet face could be partially removed, according to the inspector and based on the on-field observations, a total removal of the components of the parapet, along the length of the blockout, would be more time efficient and is usually provided with full depth removals.

- The partial demolition and replacement of the wing wall was an issue specific to Edgemoor Road, and is a rare issue that must be dealt with by those providing joint replacement/ rehabilitation services and wil subsequently not be subject to the simulation.

- The width of the deck header observed in the case study, of 2.5 feet, is larger than most deck blockouts. The width of the deck header provided in the partial depth, of 1.5 feet, is more consistent amongst the observations during the case study period and based on the experience of the professionals consulted throughout the case study.

- A full depth removal is intended to go through the full depth of concrete. The armoring system will be assumed to have been welded to the beams. on the deck header, now welded on the beams.

- The depth of concrete to be removed is to stay consistent amongst the simulations and case study observations.

4.5.3.1 **Full Depth Adjustments for Simulations**

The durations and rates attained from the case-study regarding the backwall will not be modified, in the full depth removal simulation. Anything relating to the parapet or wing walls will not be included in the simulation and all durations associated or dependent on the deck header dimensions, in any way, will have to be recalculated due its new considered geometry. Much of the concrete within the blockout is supported by the armoring systems itself, due to the length at which the abutment seat and beams are separated from one another. Also, the beam partially extends past the diaphragm without continuous support at the abutment necessitating an armoring system to have been included in the simulations. Thus all full depth simulations include an armoring system due to the geometry of the abutment.

The full depth removal of concrete headers includes the replacement of the armoring and the seal. The contractor that performed the full and partial depth joint removals and patching operations on Edgemoor Road had the option of providing an APJ, but decided against it due to the traffic patterns inhabiting the structure; also, a consultant within D.S. Brown, the manufacturer of the strip seal utilized on the site, also reiterated the same concerns regarding the APJ with regards to such traffic conditions, and concluded that the APJ would not be recommended for such a roadway.

The seal implementations will be considered separately from the full depth header reconstruction. From the initiation of demolition stage to the end of the wet curing period and the seal implementation, the full depth removal of the backwall and deck headers for the southern abutment will consist of 5 days of continuous work, 24-hours a day with 8-hour shifts work shift. As was the case in the partial demolition simulation section, it is recommended that other operations be performed on the structure due to the durations of the curing periods associated with such operations.

The periods within the construction stage and the manner at which the silicone sealants are applied will be adjusted for the full-depth replacement. There will only be 1 pour and 1 period of construction. There will be only one event of pouring of concrete into the dam, parapet base, and parapet body so as to reduce the amount of time spent curing. Thus, the wooden formwork between the parapet base and body, the dam, and all of the formwork within the dam must be completed before the first pour so that they can all be filled with Class A concrete at once. A task that was not witnessed was the pouring of silicone between the parapet and the roadway. The void between the parapet and dam must be filled with silicone, similar to the manner at which it was poured between the approach and the backwall. The backwall, however, consists of the cork formwork on top of which the silicone is poured. The void between the parapet and the roadway does not have a barrier, like the cork, over which the silicone can rest on. Thus, backer rods must be placed within the voids, adhered to the parapet/roadway interface walls with primer and then filled with the silicone applicant. Splices should be kept to a minimum with regards to the silicone sealants on the structure. Thus, the backer rod/silicone sealant combination is extended from the armoring edge, on the backwall side, to the end of the approach, totaling a length of 37.72 feet, shown in Figure 22.

Figure 22: The region of backer rod and silicone between the parapet to approach and backwall header interface to be implemented

4.5.3.2 **Full Depth Work Schedule and Total Costs**

The following tables presented in this section will be similar to those in the case-study section, providing the stage, index, task, tools used, applicant (where applicable) and the element or body of the bridge that is subject to the task in question. Also provided is the effective duration, and the scaled, expected duration. The effective duration is in worker-hours and depicts the duration expected were a laborer to work with 100% efficiency; the expected durations, in hours, are the expected amount of time that is expected for a specific task to be completed, scaled by the inefficiency factors gathered during the case study (where applicable) and the number of workers laboring. Also provided are the start and end time in 24-hour decimal format that will provide the duration of each task throughout the duration of the project. The tasks will then be organized into shifts to take into account the number of workers laboring per each shift, depending on what tasks are to be provided for each shift, in order to optimize the number of crew members on the field so as to finish the tasks as quickly as possible and reduce overhead costs of wages. The intent of the following schedules are to complete all tasks that are dependent on the work-force so as to reduce the time until concrete and adhesives need to wet-cure, which, again, are incurred durations that the work-force has no control over. The itemized, hourly schedule for the optimized full depth replacement of the dam is provided in Appendix G.

Based on the schedules of each shift provided above, the total owner, road user, and environmental impacts can be determined for the full depth header replacement. Calculated in the same manner as within the case-studies with the inclusions, exclusions, and modifications aforementioned in the section, Table 62 provides the holistic cost of a full depth replacement of an abutment expansion joint.

Table 62: Total Cost: Simulated Full Depth Removal- Total Owner, Road User, and Environmental Cost

Costing Category	Costing Components	Components' Costs	**Total Cost of Category**	Percentage of Total
Owner Costs	Wage Costs	$9,360.14	**$21,161.60**	19.06 %
	Fuel Costs	$193.21		
	Material Costs	$11,608.25		
Road User Costs	Vehicle Operating Cost	$29,073.62	**$87,006.79**	78.38 %
	Passenger Delay Costs	$57,933.17		

Environmental Costs	On-Site Power Source Env. Cost	$329.75	**$2,841.99**	2.56 %
	Vehicular Env. Cost	$2,512.24		
Total Cost		**$111,010.38**		

Thus, the accelerated full depth removal does not include the wing-wall rehabilitation from the case-study, and a reduced deck volume with backer rod implementation. The cost of the new accelerated operation, that should be more applicable to day-to-day full depth header replacements, would provide a total cost of $111,010.38, a difference of $459,017.83 from the case-study, which, as previously mentioned, is mostly due to the road user costs due to the differences in operations and optimized scheduling.

The holistic costs determined for the full depth removal and replacement of the headers must be supplemented with the holistic costs associated with the sealants that are to be positioned between the armoring. Similar to the partial depth replacement of the headers, the holistic costs associated with the acquisition and implementation of the sealants can simply be added to the total cost of the full depth replacement provided above. To the optimal header and sealant implementation schedule, the optimal header implementation schedule must first be derived.

4.6 Optimized Joint Replacement Schedule

To determine the most optimal header and sealant maintenance schedule for Edgemoor Road, the remaining life duration (in years) of the bridge must initially be determined. After determining the available years before the bridge is assumed to be reconstructed, the life expectancy of a partial depth removal and full depth replacement of Class A concrete and a partial depth replacement using elastomeric concrete must also be determined. With the life expectancies of the sealants already determined, the total simulated header maintenance, sealant maintenance, and subsequently, the total joint maintenance schedule can be determined. The simulations will begin with the adjusted full depth removal of southern expansion joint during phase 1, where a full depth removal of the headers are required and necessary due to the condition of the bridge observed during the case-study.

4.6.1 Joint and Header Life Expectancies

The manner at which headers and sealants are chosen for Edgemoor Road, is dependent on the years remaining of the bridge. The bridge was erected, as previously mentioned, to transport traffic for 50 years, after which point it is assumed that the entire bridge will be heavily rehabilitated or reconstructed. Being that the bridge was built in 1989, it is assumed that the bridge lifespan will conclude in the year of 2039 and will be considered to conclude in 2040 for simplification. Thus, the bridge will have a remaining life duration of 25 years from the beginning on July 1, 2015.

The 2009, DelDOT Pontis deterioration inventory was provided by a DelDOT representative to assist with determining the life expectancies of a partial and full depth removal of Class A concrete. Table 63 depicts the data that was provided for the life expectancy to distress level of reinforced concrete bridge decks with no overlay.

The state is the magnitude of distress embodied by the concrete structure. Thus, the median years is presumed to express the maximum life expectancy of the deck structure at each state. The possible actions one could take to improve the condition of the bridge based on the distress level can be to do nothing (DN), repair (Rpr), protect (Pro), and replace (Rplc) and are provided as options within each state range per the guidance of DelDOT. The deterioration rates and life expectancies during each state, and the duration to go from one state to another has been simplified and recreated in Table 63.

Table 63: Distress to Life Expectancy of Reinforced Concrete Deck

Distress State (%)	Life Expectancy (Years)	Cumulative Duration to Distress States (Years)	Guidance
0 to 2	8.00	8.00	DN
2 to 10	4.00	12.00	DN, Rpr&Pro
25 (=<)	2.00	14.00	DN, Rpr&Pro, Rplc

Figure 23 provides the expected duration the deck can incur as it continues to deteriorate from a 0% distress state to a distress state that is equal to or greater than 25%, in which case replacing the concrete becomes an option.

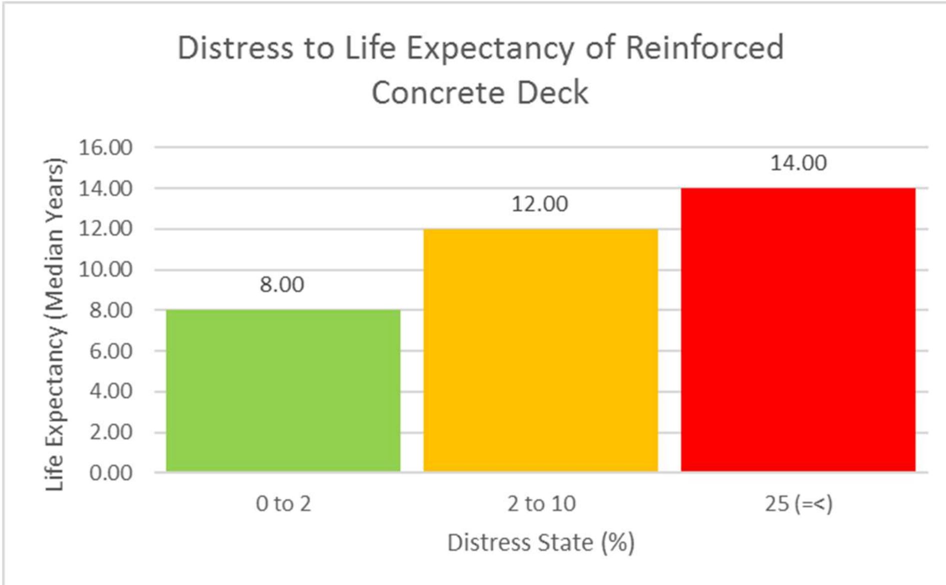


Figure 23: Distress State to Life Expectancy of Concrete Bridge Deck, Used to Model Backwall and Deck Headers

Thus, it is assumed that there will be an 8-year period, after the point in time that the headers are in perfect condition, where it is acceptable to do nothing. After the 8-year period, for a duration of 4 years, the headers can be subjected to repair, which is assumed to mean that the headers can be subject to partial depth replacement; thus, at 12 years after being in perfect condition, and without any repair actions taken in the meantime, the headers will be considered to potentially be subject to partial depth replacement of Class A or elastomeric concrete. At 14 years of no actions taken after the headers were once in perfect condition, the headers will be subject to full depth replacement of the in-place concrete with Class A concrete. It is assumed that any action taken, whether it be to rehabilitate (provide a partial depth replacement) or replace (a full depth replacement), will provide the structure with a perfect condition, or 0% distress.

The life expectancy of elastomeric concrete was determined by referring to the 2016 "Better Bridge Joint Technology" Report provided by the Department of Civil and Environmental Engineering at the University of Massachusetts and sponsored by the Massachusetts Department of Transportation (Scott A. Civjan & Brooke Quinn, n.d.). The study surveyed 9 states and received 26 respondents to understand the best practices associated with joint and header management within the Northeastern States (Scott A. Civjan & Brooke Quinn, n.d.). According to the study, elastomeric or quick setting concrete are expected to fail within 2 to 3 years within in Massachusetts (Scott A. Civjan & Brooke Quinn, n.d.). Thus, elastomeric concrete will be assumed to consist of a lifetime that is 3 years in duration. The durations (in years) until certain actions are to be taken with regards to doing nothing, partially replacing Class A or elastomeric concrete, or fully replacing Class A concrete are shown in Table 64.

Table 64: Expected Duration Until Action to be Taken

Action	Duration Until Action from 0% Distress (Years)	
	Class A Concrete	Elastomeric Concrete
Partial Depth Replacement	12	3
Full Depth Replacement	14	-

4.6.2 Joint Header and Sealant Maintenance Schedule

With the life expectancies of the varying types of header replacement determined as well as the duration at which certain actions can be taken, a header maintenance schedule can be determined. As previously mentioned, the sealant maintenance schedule is dependent on the header maintenance schedule; thus, the optimal header maintenance schedule must first be determined.

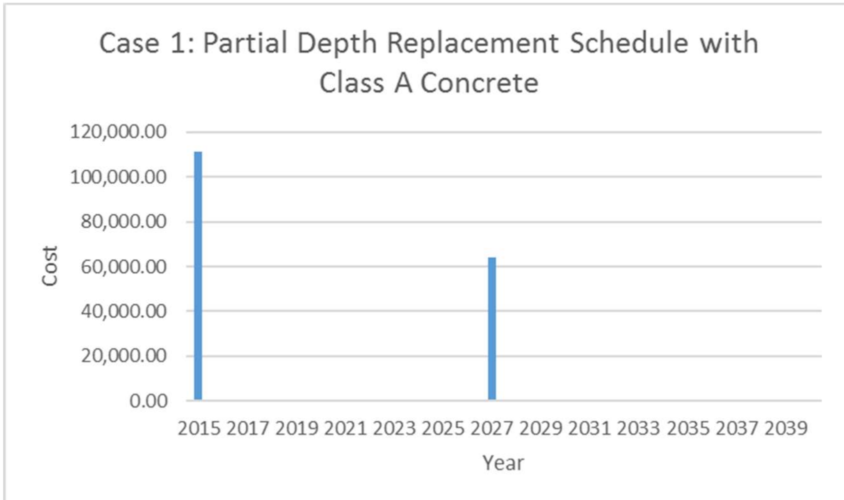
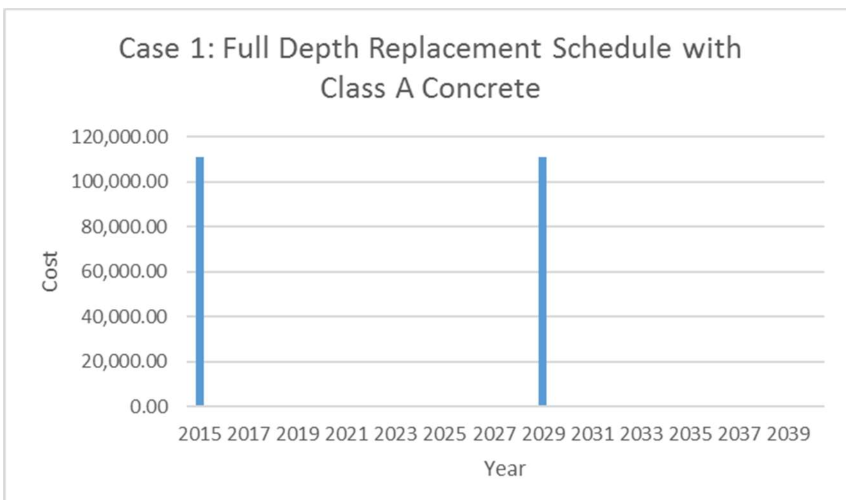
4.6.2.1 **Joint Header Optimized Schedule**

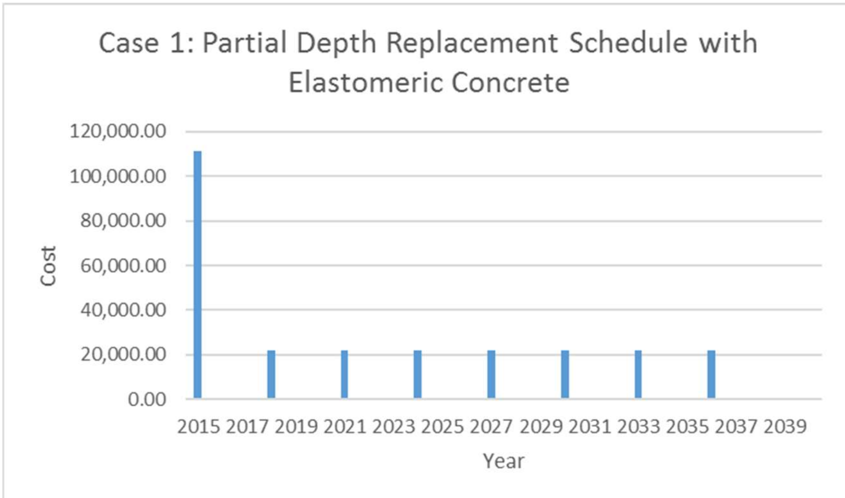
It is important to determine when, and if, a full depth replacement or partial depth replacement should take place during the remaining 25 years left until the bridge is considered to reach the end of its design life. With the full depth replacement performed in 2015, no action is considered to be taken until 2027 (12 years after the new concrete is fully implemented). In 2027, the headers can be repaired or not. If it is decided that the headers should be partially replaced, the decision maker must decide whether to implement Class A or elastomeric concrete. If it is decided that no action is to be taken until the headers are to be fully replaced, the replacement action would take place in 2029 (14 years after the initial full depth replacement). Within the time frame available, one partial depth replacement that occurs in 2027 restores the health of the headers and provides it with 14 extra years until it would have to replaced again in 2041, 1 year after the entire bridge would be considered for reconstruction or heavy rehabilitation. Thus, one partial depth replacement of the concrete with class A concrete would provide functional headers until the bridge's lifespan is complete. Thus, a full depth replacement, applied in 2029 would provide the headers with adequate strength until 2043, 2 years after the designed 50-year period.

Being that a partial depth replacement is cheaper than a full depth replacement, it would be in the benefit of the agency to provide a partial depth replacement in 2027 than waiting until 2029 to provide a full depth replacement. Referring to the previous simulations, a partial depth and full depth replacement would cost $175,261.82 and

$222,020.75, respectively. Thus, when juxtaposing the options of providing a full depth and partial depth replacement of Class A concrete within the range of the structure's remaining life, a partial depth removal would be financially more favorable by $46,758.93.

A partial depth replacement of concrete with elastomeric concrete would occur every three years were such a quick-cure admixture to be implemented. With a curing time of one-hour and a life expectancy that is understood to be less than that of a mixture such as Class A concrete, agencies often view such quick-cure mixtures as a necessary cost saving technique, though compromising the life expectancy of patches and headers, when keeping traffic congestion in mind. However, the overall agency, societal, and environmental costs actually exceed the costs of a full depth removal due to its 3-year life expectancy. It was calculated that the holistic cost to implement the elastomeric concrete during a partial depth replacement, once, is $22,204.57, $42,046.87 cheaper than using Class A concrete for a partial depth replacement, and $88,805.80 cheaper than a full depth removal. The holistic cost over the remaining life of the bridge, however, utilizing elastomeric concrete, would come out to $266,442.38, $91,180.56 more expensive than providing a partial depth replacement with Class A concrete, and therefore $44,421.63 more expensive than a full depth replacement. Figure 24 and Table 65 provide the graphical and numerical juxtaposition of each headers proposed maintenance schedule and their associated costs.

	**Total Cost= $175,261.82**
	Total Cost= $222,020.75



Total Cost=
$266,442.38

Figure 24: Partial and Full Depth Resultant Schedules and Costs for Remaining Lifetime of Bridge Template Structure

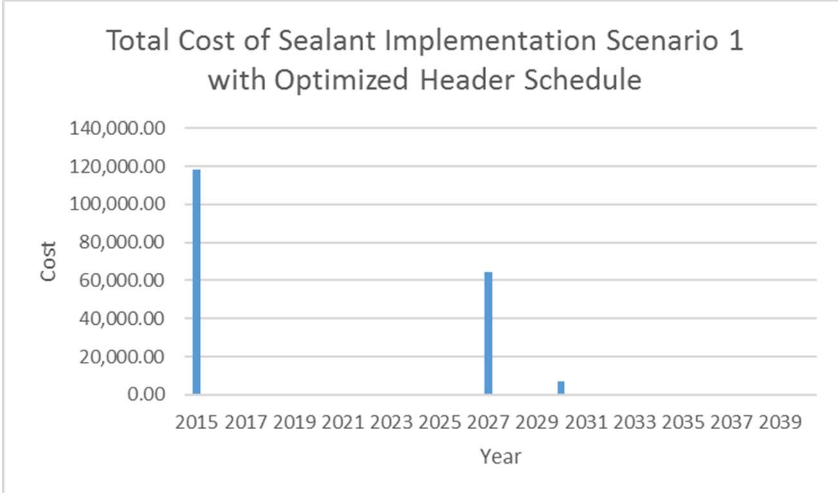
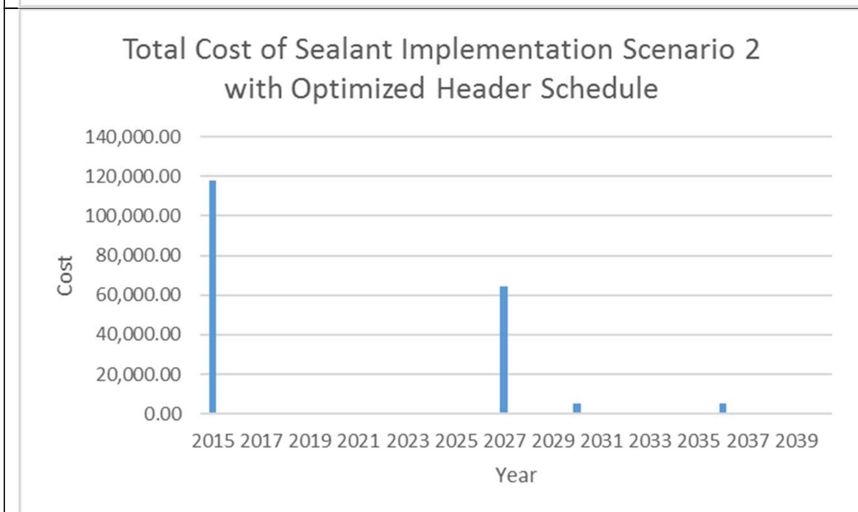
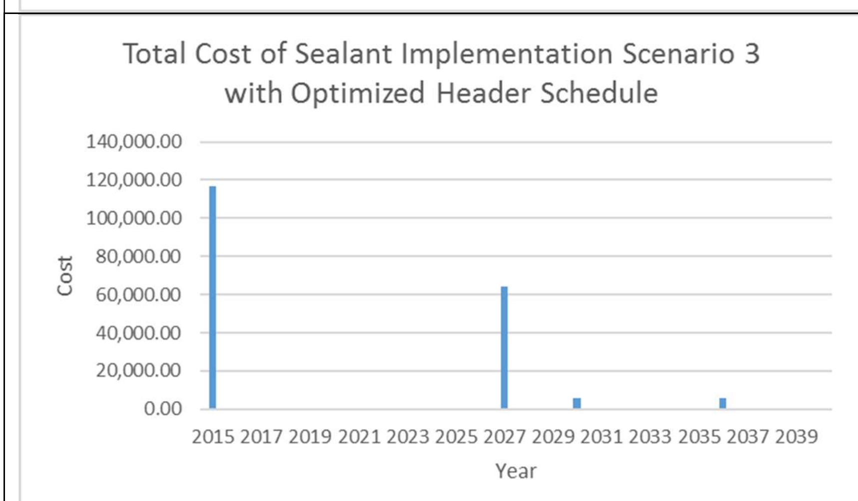
Table 65: Joint Maintenance Schedule Costing Scenarios

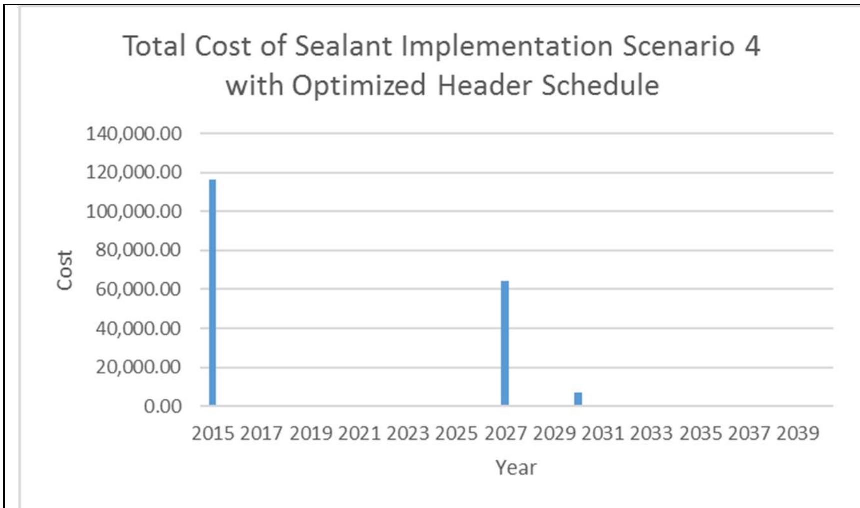
Scheduling Scenario	Cost
Full Depth Replacements	$222,020.75
Partial Depth Replacements with Class A Concrete Cost	$175,261.82
Partial Depth Replacements with Elastomeric Concrete Cost	$266,442.38

Thus, the most cost efficient option, with regards to the agency, societal, and environmental costs, is to have fully replaced the concrete headers in 2015 and partially replace the concrete headers with Class A concrete in 2027.

4.6.2.2 **Joint Sealant Optimized Schedule**

Since there will only be one full depth replacement, during the year of 2015, sealants will only have a life expectancy associated with "new construction" once; all other sealant replacements will therefore be considered as "rehabilitative" actions to the expansion joint system. After simulating the overall costs associated with implementing the CCF and VS, it has been determined that such sealants should never be implemented as the SS and OCS are both cheaper and embody a longer life expectancy than the CCF and VS. There are 4 possible combinations that SSs and OCFs can be implemented during the remaining lifetime of the bridge template structure after the full depth replacement of the headers. The costs associated with the 4 scheduling simulations of the sealants have been added to the schedule and costs simulated with the optimized partial depth header replacement (with Class A concrete), and have been shown, graphically and numerically, in Figure 25 and Table 66, juxtaposing the total costs of the 4 header/sealant combinations. Note that the first costs in 2015, in all 4 simulations, is a combination of both the full depth removal and the optional sealant implementations. All other costs in the remaining 3 simulations were consistent with a partial depth removal of Class A concrete and sealant(s) replacements that were out of phase with one another.

	**<u>Sealant Scenario (1):</u>** • SS (New) • SS (Rehab) **<u>Total Cost=</u>** $189,420.05
	**<u>Sealant Scenario (2):</u>** • SS (New) • OCS (Rehab)**X2** **<u>Total Cost=</u>** $193,449.20
	**<u>Sealant Scenario (3):</u>** • OCS (New) • OCS (Rehab)**X2** **<u>Total Cost=</u>** $191,924.21



Sealant Scenario (4):

- OCS (New)
- SS (Rehab)

Total Cost= $187,895.07

Figure 25: Juxtaposition of Total Optimized Joint Maintenance Schedule per Sealant Schedule Scenario

Table 66: Sealant Implementation Scenarios and Total Cost with Optimized Header Schedule

Sealant Imp. Scenario	Sealants Implemented	Total Cost Over Remaining Lifetime ($)
1.00	**SS(New), SS(Rep)**	**189,420.05** (2)
2.00	SS(New), OCS(Rep)X2	193,449.20
3.00	OCS(New), OCS(Rep)X2	191,924.21
4.00	**OCS(New), SS(Rep)**	**187,895.07** (1)

The most cost effective joint maintenance program includes the full depth removal of the headers in 2015, and a partial depth replacement of the headers with Class A concrete in 2027; the OCS is to be newly implemented after the full depth replacement and the OCS is to be removed and replaced with a SS in 2030 (scenario 4) for a total joint maintenance cost of $187,895.07 for the remaining life of the bridge structure template.

The life expectancies of the OCSs are comparable to those of the SS though many agencies have made it a point that they are phasing out OCSs due to their sporadic failure behaviors. Alternatively, the second lowest joint maintenance cost, or scenario 1, would provide a SS after the full depth removal, and, after the SS is removed in 2030, it would be replaced with another SS. The difference in costs between scenario 1 and scenario 4 is only $1,524.99, and may be worth the cost to reduce the variability of failure.

Chapter 5

DISCUSSION

5.1 Summary of Analysis

To determine the optimized joint replacement schedule for the case-study template, the following had to be determined,

- Case-Study Total Costs
- Optimized Full Depth Replacement Total Costs
- Optimized Sealant Replacement Total Costs
- Optimized Full Depth Replacement Total Costs

Based on the durations and rates attained from the case-study, adjustments were made to task sequences that were observed as well as the expected durations of said tasks to make the results more applicable to other studies. Thus, anomalous data from the LCI was excluded. After adjustments were made, the optimized full depth, partial depth, and sealant replacement schedules were simulated and the owner, societal, and environment impacts and costs were determined. After the schedules of the varying maintenance actions were determined, complimented with knowledge of the life expectancies of all of considered header and sealant types, an optimized schedule for future maintenance actions for the abutment expansion joint could be simulated. The type of sealant, and whether it would be posses the life expectancies associated with “new construction” or “rehabilitation” was entirely dependent on the forecasted header replacement schedule, since a full depth replacement would necessitate the implementation of a newly constructed sealant. Once the optimal header replacement schedule was determined, the sealant replacement schedule was then decided upon; thus, the most cost effective joint maintenance program includes the full depth removal of the headers in 2015, and a partial depth replacement of the headers with Class A concrete in 2027; the OCS is to be newly implemented after the full depth replacement and the OCS is to be removed and replaced with a SS in 2030 (scenario 4) for a total joint maintenance cost of $187,895.07 for the remaining life of the bridge structure template.

5.2 Important Results

The results of the analysis chapter agree with many of the resources in the literature survey, in that preventive maintenance programs are the more efficient than reactionary, or heavily rehabilitative, programs. In the simulations, a partial depth replacement with Class A concrete is considered to provide preventive maintenance services while the full depth removal is to provide reactionary maintenance, due to the fact that the duration at which a full depth removal may occur, is the same time at which the headers can no longer service the traffic. A partial depth and full depth replacement would cost $175,261.82 and $222,020.75, respectively. Thus, when juxtaposing the options of providing a full depth and partial depth replacement of Class A concrete within the range of the structure's remaining life, a partial depth removal would be financially more favorable by $46,758.93.

By considering the total owner, user, and environment impacts, the schedules were accelerated to reduce the societal costs (road user costs). By accelerating the schedule to occur over a 24-hour period, that does not include the wing-wall rehabilitation from the case-study, and a reduced deck volume with backer rod implementation the cost difference between the case-study and the accelerated schedule is vastly different. The cost of the new accelerated operation, that should be more applicable to day-to-day full depth header replacements, would provide a total cost of $111,010.38, a difference of $459,017.83 of the total cost of the case-study.

The partial depth replacement using elastomeric concrete option is also considered to be a reactionary maintenance action. As previously mentioned, throughout the case-study many contractors raised concerns with using elastomeric concrete due to its short life expectancy; many felt obligated to use such admixtures though they knew that such a solution would prove to be very temporary. On larger roadways where contractors are not allowed limitless time to complete their tasks, the contractors used such admixtures due to the time limit of lane closures imposed on them by the DOT. Elastomeric concrete is in fact far costlier to each of the three pillars, due to short durational cycles at which they must be removed and replaced again. Initially the cost to partially demolish and replace concrete with elastomeric headers are much cheaper, but in the long run it can become much costlier. It was calculated that the holistic cost to implement the elastomeric concrete during a partial depth replacement, once, is $22,204.57, $42,046.87 cheaper than using Class A concrete for a partial depth replacement, and $88,805.80 cheaper than a full depth removal. However, the holistic cost over the remaining life of the bridge, utilizing elastomeric concrete, would come out to $266,442.38, $91,180.56 more expensive than providing a partial depth replacement with Class A concrete, and therefore $44,421.63 more expensive than a full depth replacement. Though it is positive sign that DOT's consider the effects of lane closures on certain roadways, it is in the department's best interests to forecast future maintenance/rehabilitation actions based on the decisions to be made; in doing so longer construction periods than those expected by the usage of elastomeric concrete would most probably be allowed, ensuring that the actions provided by contractors on the field are also cost efficient in the long run.

The environmental costs are quite low compared to the owner costs while the road user costs are, comparatively, extremely high. Table 67 provides the percentage of the total costs that the owner, societal, and environmental costs represent during the case study, simulated partial depth replacement, simulated full depth replacement, and the average simulated sealant (OCS and SS) replacements.

Table 67: Owner, Societal, and Environmental Cost Percentages of Total Costs for Case Study and Simulations

Costing Parameter	Case-Study Costs	Partial Depth Replacement Simulation	Full Depth Replacement Simulation	Sealant Replacement Simulation (Average)	Average	Standard Deviation
Owner Cost	6.67 %	8.29 %	11.62 %	15.73 %	10.58 %	2.52 %
Societal Costs	90.61 %	88.97 %	85.66 %	81.91 %	86.79 %	2.52 %
Environ. Costs	7.72 %	2.74 %	2.72 %	2.36 %	3.89 %	2.88 %

As can be seen in Table 67, the percentages of the averaged owner, societal, and environmental costs are 10.58%, 86.79%, and 3.89%. The averages are quite consistent throughout all of the analyses and simulations provided in Table 67. The aforesaid averages do not deviate from one another by much; the owner, societal, and environmental costs have standard deviations of 2.52%, 2.52%, and 2.88%, respectively. Thus, despite accelerating the schedule and reducing the total overall costs, the societal costs were just as dominant in the simulation as they were in the case-study, and the environmental costs were just as ineffective. The majority of the costs calculated were due to the road user delay and vehicle operating costs on detours. It is recommended that during construction processes, the phases at which construction proceeds throughout a bridge be provided in small intervals so that, if possible, entire directions need not be detoured.

It is difficult to determine whether or not the environmental impacts determined are accurate, underestimated or overestimated due to the fact that, even between various sources that have attempted to cost emissions, there are major discrepancies. More research is needed to cost emission per pollutant type and a general consensus must be established. Another issue is the fact that the societal (road-user) costs are so much larger than the owner costs. If user and environmental costing are to be implemented in future projects, the issue of how to scale said costs is of concern. By implementing the A+B+C bidding process, DOT's will be responsible for determining correct environmental costing factors and a strategy in scaling environmental and societal impacts into the bidding process.

It is important for DOT's not only to begin looking long-term when imposing restrictions on the contractors, but that they also necessitate A+B+C costing, for all road-types and maintenance actions, in their bidding process. The DOT's should provide each contractor with a template, or program, so that they may calculate the B+C costs based on the location of the project, the tasks within the project, and its duration. By implementing B+C costing into the bidding process, and by being responsible for giving the tools to estimate such costs, it will become the responsibility of the DOT's to spearhead the implementation sustainable construction and maintenance programs through total costing. The DOT's must therefore spearhead state-wide monitoring of traffic conditions in work-zones, and create an inventory database of emission estimates for normal and work-zone conditions (as well as their costing parameters) dependent on the location of the project as well. One cannot expect the contractor to be totally responsible for compensating all of the costs incurred through road user and environmental costs as it may affect the quality of their work, as can be seen through the usage of elastomeric concrete. The user and environmental costs must be scaled as they are astronomically disproportionate to the owner costs usually bid on; the scaling, however, should catalyze incentives to practice LCA's and sustainable maintenance and construction practices.

Sustainable strategies and construction, such as those suggested in this paper, circumvent the undesired consequences incurred to the society and the environment through traditional uninformed construction practices. It is the right of the people to request that DOT's implement progressive strategies to lower road-user delays, vehicle operating costs, and environmental emissions due to the fact that taxes usually fund such practices. If there are alternative construction practices that minimizes the long term costs experienced by the general population, which there are, it is the right of the general population to expect that such costs be minimized if possible, which it should be. In fact, one could make the point that it is the responsibility of DOT's to provide strategies and redefine practices that will lower the overall costs incurred to the owners, society, and the environment.

BMSs should support the user costs, environmental costs, and owner costs for smaller features of the bridge structures, especially the joint and its headers. To simulate the life expectancies of the partial and full depth removal of the headers, DelDOT's Pontis database was referred to. The database did not have data on headers, thus leading to the usage of the distress to life expectancy data regarding reinforced concrete roadway with no overlay. The joint headers, though a part of the reinforced concrete deck, is more vulnerable than the rest of the riding surface due to the disruption in surface continuity; consequently, the number of impacts it experiences, and the fact that it is less supported than the rest of the deck, necessitates that such components have their own deterioration models. Distress to life expectancies of full depth and partial depth concrete headers replacements, with armoring and without armoring, should be included in the BMSs as should the usage of quick curing admixtures such as elastomeric concrete.

To provide a pseudo-LCA study, such as the one created in this research endeavor, those conducting the study are compelled to create a more elaborate inventory than a LCCA does. Such a dense inventory is necessary in the pseudo-LCA approach due to the environmental and societal impacts of the study that must be nominalized or monetized. With a greater variety of tasks and materials observed, a larger variety of rates can be utilized to simulate a larger variety of tasks; the degree and applicability of a LCA is only as great as the vastness of the assembled inventory.

Chapter 6

CONCLUSION

Based on the durations and rates attained from the case-study, the optimized full depth, partial depth, and sealant replacement schedules were simulated and the owner, societal, and environment impacts and costs were determined. After the schedules of the varying maintenance actions were determined, complimented with knowledge of the life expectancies of all of considered header and sealant types, an optimized schedule for future maintenance actions for the abutment expansion joint could be simulated. The type of sealant, and whether it would be possess the life expectancies associated with "new construction" or "rehabilitation" was entirely dependent on the forecasted header replacement schedule. A full depth replacement would necessitate the implementation of a newly constructed sealant. Once the optimal header replacement schedule was determined, the sealant replacement schedule was then decided.

The most cost efficient joint maintenance program determined for the remaining life of the Edgemoor Road Bridge includes the following:

- A full depth removal of the headers in 2015,
- A partial depth replacement of the headers with Class A concrete in 2027;
- For the sealants, the strip seal is to be newly implemented after the full depth replacement and the open compression seal is to be removed; and
- The open compression seal is to be replaced with a strip seal in 2030 or a total joint maintenance cost of $187,895.07.
- The most expensive joint maintenance program includes a full depth removal of the headers in 2015, and 7 partial depth replacement of

the headers with elastomeric concrete; the headers replacement schedule would be supplemented with a new strip seal implemented in 2015 and open compressions seals implemented in 2030 and 2036. The most expensive option would cost approximately $285,000.00, approximately 52% more expensive than the optimized program. Within each program considered the owner costs ranged between 10-15% of the total costs, the societal costs ranged between 80-90% of the total costs while the environmental costs ranged between 2.6 and 2.7% of the total costs.

The results support preventive maintenance, a trend that is growing amongst agencies today, as the more cost effective to understand how elements deteriorate and provide services that retards deterioration before major construction or rehabilitation is necessary.

One concern that came up during the case-studies was the health of the workers. Many of the laborers struggled with constant pain due to the physically intensive labor, especially those who were older. Also, many of the workers were subject to fumes, abrasives, and small pollutant particles; essentially, the workers were directly exposed to an ample amount of the environmental impacts created and calculated from the field. It is necessary that construction equipment begin to be designed and developed for workers that impose less physical stress on them and that innovations be developed that can assist in minimizing pollutant exposure that such workers are faced with, in high amounts, on a daily basis. The monetized impacts developed do not capture the impacts to the workers that regularly inhale such pollutants well. Regrettably, if the costing factors for health impacts from pollutant emissions used better reflected the more direct exposure experienced by workers, it would most likely be noticeably higher. In the future, environment costs could be determined to reflect the health impacts incurred by workers, and innovations and construction equipment could be developed to lower such costs and impacts.

Transportation agencies spend millions of dollars to maintain, rehabilitate, and replace expansion joints each year through a variety of actions taken. However, there is often a lack of reliable values that decision makers can refer to when faced with choices regarding header and sealant types. It was determined that BMSs must be expanded to include more information to support the simulations and analyses of the outcomes or impacts of tasks associated with maintaining, rehabilitating, and reconstructing deck expansion joints. With more informed decision making based on collected performance data, bridge owners would in return be able to make decisions that would result in more efficient practices - lowering costs and impacts of rehabilitation and replacement to themselves as well as to the users of the structure.

This research effort acquired data from construction sites to provide holistic costs. Such values can be utilized to provide more efficient and sustainable practices with regards to bridge expansion joints in BMSs. Though more studies would more finely determine how such durations and rates vary between contractors, the rates determined through this research can be used as a starting point for improving BMS decision-making about joint replacement costs to owners, users, and the environment.

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Appendix A

DEMOLITION ACTIONS DURATIONS AND RATES

The dam is composed of the backwall and deck headers. The backwall, sits on the bridge abutment seat, and longitudinally extends 1 foot from the approach roadway. The backwall and the approach roadway are their own structural compartments that are separated by an epoxy joint, allowing for another outlet for expansion and contraction between the backwall and the approach. Thus, the entirety of the backwall accessible to the construction crew was demolished to a depth of 1.25 feet (to the top of the abutment seat). The deck header was measured to be 2.5 feet, longitudinally, from the joint reservoir to the deck header wall. The deck header wall is the interface between the demolished concrete and left in place concrete. The volumes determined for the parapets included the body of the parapets themselves (the portion of the parapets that extend upwards from the riding surface), the base (the depth of the backwall and deck headers of 1 foot) and the portion of the wingwall volume on the backwall side of the dam. Figures 26-28 show the dam headers before, during, and after demolition and Figures 29-31 depict the parapet and wingwall also before, during, and after the demolitions stage.

Figure 26	The Dam, and Previous Joint System Pre-Concrete Sawing	Figure 27	The Dam After 4 Days of Demolition	Figure 28	The Dam After 5 Days of Demolition, Now Prepped for Construction

Figure: 26-28: Dam Demolition Progression from Pre-Demolition to Pre-Construction

Figure 29 The Wing Wall Previous to Any Demolition

Figure 30 Demolition of the Parapet with a Clear Depiction of the Overhang since the Deck Pan was Punctured by the Skid Steer Loader

Figure 31 The Completion of the Parapet and Wing Wall Demolition

Figure 29-31: Parapet and Wing Wall Demolition Progression from Pre-Demolition to Pre-Construction

Before demolition could begin, the perimeter of the dam to be demolished had to be saw cut. Saw cutting of the dam was completed by a contractor before the arrival of the total work crew. The backwall header did not need be saw cut because the backwall is only sits on the abutment seat and is disjointed from the approach. The deck header, however, had to be saw cut as can be seen in Figure 32.

Figure 32: Pre-Construction, Deck Header Segmentation Through Concrete Saw Cutting with the Walk-Behind-Saw

A.1 Dam

The backwall was demolished with thirty pound pneumatic breakers. The number of breakers ranged from one to three, depending on the day and the availability of other crew members. The backwall was so deteriorated that, for the first day, along with breaking, one worker was able to dig up the concrete with a shovel due to the magnitude of deterioration on the parts of the backwall near the parapet Figure 33-34.

Figure 33 The Dam Post-Concrete Saw Cutting and Pre-Construction. Notice the Welded Plates on the Armoring and the HMA

Figure 34 Depiction of the Malleability of the Backwall Header (HMA) Excavated through the Use of a Shovel

Figure: 33-34 Depiction of the Poor Physical Condition of the Backwall Previous to Demolition

It should be noted that a distinction is made when referring to the armoring and the armoring system. The armoring is referred to as the metallic pieces of the armoring system that is noticeable on any armored joint, collinear with the riding surface. The rest of the armoring system is referred to as the armored anchorage system that anchors the armoring to the backwall and deck. The armored anchorage system was drilled and epoxy'd into the backwall abutment seat and welded on the diaphragm on the deck side of the dam. The armoring is composed of one piece of steel that forms a right angle, forming two lips. The armoring is connected to the armoring anchorage system through brackets. In practice, the anchorage system of the deck header should have been welded to the beam and not the diaphragm due to the fact that the diaphragm is subjected to replacement more so than the beams. In the construction stage of phase 1, 10 anchorage systems were welded to the beams on the deck side of the dam and 5 anchorage systems were drilled and epoxied into the abutment seat as can be seen in Figure 35-36. The previous sealant already had detached and was easily spliced and removed from the joint reservoir as can be seen in Figure 37.

Figure 35 Depiction of Deck Header (10) and Backwall (5)

Figure 36 Depiction of the Deck Header (5) and Backwall (10) Anchorage

Anchorages Arrangements from Previous Construction

Arrangements During the Construction Stage

Figure: 35-36: The Reversal of the Anchorage Arrangements from Erection of the Bridge to Reconstruction of the Expansion Joint and Headers

Figure 37: Removal of the Previous Cushion Joint Seal

The breakers essentially began demolition at the base of the parapet and worked outwards towards the median where the concrete was harder and more stable. While breaking occurred, the foreman used a torch to heat cut the webs of the armored joint anchorage system, or brackets, when the depth of concrete demolished allowed him to do so. The lips of the armoring were also cut and the armoring was segmented and removed as can be seen in Figures 38-39, to allow more room for further demolition. By segmenting the armoring, it could be detached in smaller pieces that could be removed either with the skidder or by hand without halting all other operations on the dam as can be seen in Figure 40.

Figure 38 Heat Cutting/Torching of the Armoring

Figure 39 Segmented Armoring, (with Torch), Momentarily to be Detached when Banged with Breaker

Figure 40 Removal of Armoring with Skid Steer Loader

Figure: 38-40: Heat Cutting/Torching of the Armoring and Brackets, and Removal of the Armoring

Along with cutting of the anchorage system, the torch was also used to cut the existing rebars and dowels sticking out of the dam; removal of the existing steel stay-in-place form, referred to as the formwork can be seen in Figure 41. Formwork contains the wet concrete and keeps it from spilling out of the designated area of intended pouring until it dries.

Figure 41: Torching and Removal of the Previous Metal Formwork

After the concrete was completely demolished, the armoring anchorage was removed through heat cutting as well. It is important to keep in mind, as aforementioned, that the heat cutting of all of the armoring system, formwork, and rebars did not all occur at once; procedurally such tasks were completed by the foreman and completed when such entities were accessible as can be seen in Figure 42. Dimensionally, the heat cutting was considered to be done over the length of the dam, width of all the brackets, and the perimeter of all of the armoring anchorage systems that were welded to the diaphragm.

Figure 42: Heat Cutting/Torching Performed Intermittently as Soon as Armoring Elements Made Available to Foreman

It was the crew's intent that both the backwall and the deck header be completed at the same time. The deck header was broken with a 30-pound pneumatic breakers and the skid steer loader, due to its vastness. The skidder was equipped with a Bobcat HB980 hydraulic breaker attachment. The HB980 attachment translated to, approximately, a 500 pound operating weight, accelerating the breaking process (Dooson Benelux S.A./N.V., n.d.) on the deck header. The deck header was demolished, initially, with the skid steer loader while the workers using the thirty-pound pneumatic breakers worked on the demolishing the backwall as can be seen in Figure 43. Thus, to ensure that the skidder did not impact the diaphragm and beams underneath the concrete, it was important that the skid steer loader stopped breaking at a certain depth (per the operator’s discernment) after which the thirty-pound pneumatic breakers would take over as can be seen in Figure 44.

Figure 43: The Skid Steer Loader Breaking on the Deck Header While 30-Pound Breakers Are Utilized on the Backwall

Figure 44: Usage of the 30 Pound Pneumatic Breakers on the Deck Header After Breaking with the Skid Steer Loader Ended

It should be noted that the DelDOT bridge maintenance manual does not allow for any breaking tools that are heavier than 30-pound breakers to demolish the concrete. After a DelDOT project manager was contacted regarding this issue, it was determined that the aforesaid rule was written with the assumption that sawing into the concrete would not be cut as deep as the eight inches provided on the field. Thus, breaking with the skid-steer loader deemed acceptable.

A.2 Parapet

Though the parapet was subject to breaking intermittently during the demolition of the dam, the parapet was focused on, continuously, after the dam was demolished. If more workers were on the site with another air compressor, the demolition of the parapet and wingwall could have occurred even before the demolition of the dam. The demolition of the wingwall and parapet was independent of the dam. The skidder was also used to break the erect portion of the parapet, and not its base, nor the wingwall. The rates utilized for the dam are not applicable for the parapet as the thickness of the concrete being broken and its ease of access greatly influence the rate of demolition. The parapet was segmented with the concrete saw to accelerate the breaking process..

The wingwall, parapet base, and parapet body was, like the dam, subjected to breaking by both the 30 pound breakers as well as the skidder as can be seen in Figures 45-46.

Figure 45: Parapet Body Subjected to Breaking from Skid-Steer-Loader

Figure 46: Wing Wall, and the Parapet Base Subjected to Breaking from the Thirty Pound Breaker

All of the tasks, dimensions, and rates discussed have been implemented into Table 5. Some tasks were capable of being consolidated. For example, the torch was used to provide the following incremental tasks throughout the demolition stage

- Segment the armoring and detach it from the armoring system
- Detach the old formwork from the exposed beams and diaphragms
- Detach those steel reinforcements bars that were not broken from the dam during the demolition stage

Instead of calculating the durations and rates associated with each finite task, individually, which can be highly dependent on personal, instinctive and even emotional factors, the durations were accumulated and combined when possible. The durations for torch/heat cutting were combined to equal 3.52 hours to complete all associated tasks, indicated by index 9 in Table 69, to be discussed. The duration was provided as the quotient when determining the completion, or demolition, rate during this stage and the dividend was determined to be 56.55 feet, the sum of the anchorage system (the perimeter of all anchorage systems that were heat), total steel formwork length, and total bracket lengths in feet, equating to a rate of 16.08 Linear Feet/Worker-hour.

Before presenting the durations and rates, the nomenclature employed within the data tabulation and inventory must first be expressed. Table 68 provides terminology that can be seen throughout the entire inventory spanning stages,

Table 68: Descriptions of Terminology Used in Task Description, Duration, Duration Rate and Rate Dependency Tabulations

Units	Description
Applicant	A column relevant only during the construction stage, applicants indicate the dissemination of particular materials from the tool to the bridge component, or more specifically, the component's element
Blockout	
Bridge Component	General Designation of Task Occurrence Location
Bw	Backwall
By Hand	Indicates the usage a of non-motorized instrument as the tool designation in completing the task
C	Referring to index designation: "C" refers to the specification that the index preceding the task in question must be completed for the current task to begin.
CF	Cubic Foot
Cnsmbl	Consumable Task Duration- A task that would be implemented to any joint replacement operation of that specific duration regardless of the magnitude of said operation. The duration of such a task is not scaled and the magnitude of its application is diurnally, binary.
Component's Element	The specific location within the location, or entity, of the bridge component in question
Construction	
Excavating	Demolition-Shoveling demolished or soft concrete "By Hand"
Formwork	
Handheld Saw	Self-powered, handheld concrete saw for intermittent, shallow concrete sawing during on-field operations
I	Referring to index dependency: "I" refers to the specification that the index preceding the current, dependent, task should have begun; however, the current task can be completed simultaneously, or intermittently, while completing the independent task.
Index	The order at which tasks were completed on the field
Index Dependencies	For simulation purposes: The earliest possible commencement of a task, Indictaed by the Index of the preceding task, i.e. "Index Dependencies". Index Dependencies are followed by a "(C)" or "(I)", specifying whether the task referred to must be completed before the commencement of the task in question.
LF	Linear Foot

WHr	Worker-hour
Pp	Parapet
Rate	The rate of task completion in the associated units under the pursuit of completing the associated stage
SF	Square Foot
Skidder	Skid Steer Loader
Steel Reinforcement	Armoring System [Anchorage (welded and bolted), Armoring, Brackets] and Rebar
Tool	Tool with which tasks were completed
Torch	Tool- Connected to Oxygen and Acetylene Tanks, tasked with Performing Torch/Heat Cutting
TPB	Thirty-Pound-Pneumatic-Breaker
Unt	Unit of material, as opposed to some sort of dimensions, utilized in determining a rate for the relevant task duration
Walk Behind Saw	Walk-behind concrete saw utilized in sectioning the deck blockout, indicating the initiation of the joint replacement endeavor observed

Table 69 provides all demolition tasks, in general order of completion, with their associated durations, and completion rates.

Table 69: Demolition Task Descriptions, Durations, and Rates from the Initiation of the Case-Study to the Initiation of the Construction Stage

Stage	Index	Task	Tool	Component's Element	Bridge Component	Index Dependence	Duration (Worker-hours)	Rate	Unit
Demo.	1	Sawing	Walk Behind Saw	Concrete	Dam	-	0.80	53.64	Ft/WHr
Demo.	2	Sawing	Handheld Saw	Concrete	Parapet Body	-	0.18	Cnsmbl	Cnsmbl
Demo.	3	Breaking	TPB	Concrete	Backwall	1(C)	24.87	1.98	CF/WHr
Demo.	4	Breaking	Skidder	Concrete	Deck	1(C)	4.31	10.81	CF/WHr
Demo.	5	Breaking	TPB	Concrete	Deck	4 (I)	12.08	1.98	CF/WHr
Demo.	6	Breaking	Skidder	Concrete	Parapet Body	5(I)	0.17	130.82	CF/WHr
Demo.	7	Breaking	TPB	Concrete	Parapet Base + Wing Wall Volume	6 (C)	2.52	6.83	CF/WHr
Demo.	8	Excavating	By Hand	Rubble	Dam	3(I), 4(I)	9.03	17.57	CF/WHr
Demo.	9	Torching	Torch	Steel Reinforcement+ Form Removal		3(I)	3.52	16.08	LF/WHr
Demo.	10	Removing	By Hand	Rebar	Parapet Body	6(C)	0.38	Cnsmbl	Cnsmbl
Demo.	11	Smoothing	Grinder	Beam	Superstructure	12(C),13(C)	0.45	22.22	Unt/WHr
Demo.	12	Smoothing	Grinder	Diaphragm	Superstructure	12(C),13(C)	1.00	39.41	Ft/WHr
Demo.	13	Removing	Saw	Strip Seal	Dam	-	0.02	Cnsmbl	Cnsmbl

Table 70, further specifies the rates determined for each task, based on the task title and index number, for reference purposes. With the duration, determined above for each task, as the quotient in all of the following rates, the dividend is defined in Table 70 by its name/description, value, and unit.   The power source is also provided, for, as will be determined, the rate of usage will not only impact the demolition, construction, and cleaning durations, but also the magnitude of pollutants emitted, and fuel usage as well as their associated costs. The associated power sources have been discussed in the costing formulation sections.

Table 70: Rate Dependency Descriptions, Values and Power Sources Associated with all Demolition Tasks

Stage	Index	Task	Tool	Component's Element	Rate Dependence	Dependence Value	Unit	Power Source
Demo.	1	Sawing	Walk Behind Saw	Concrete	Total Sawed Length	42.91	ft	Walk Behind Saw
Demo.	2	Sawing	Handheld Saw	Concrete	Cnsmbl	Cnsmbl	Cnsmbl	Handheld Saw
Demo.	3	Breaking	TPB	Concrete	Bw Volume Demo'd	49.26	ft^3	Air Compressor
Demo.	4	Breaking	Skidder	Concrete	Deck Volume Demo'd	46.57	ft^3	Skidder
Demo.	5	Breaking	TPB	Concrete	Deck Volume Remaining After Skidder	23.94	ft^3	Air Compressor
Demo.	6	Breaking	Skidder	Concrete	Total Parapet Body Volume	21.80	ft^3	Skidder
Demo.	7	Breaking	TPB	Concrete	Total Demolished Parapet Base and Wing Wall Volume	17.18	ft^3	Air Compressor
Demo.	8	Excavating	By Hand	Rubble	Total Demolished Dam Volume	158.75	ft^3	-
Demo.	9	Torching	Torch	Steel Reinforcement+ Form Removal	Metal Formwork+ Armoring+ Anchorage(Deck)+ Brackets	56.55	ft	Torch
Demo.	10	Removing	By Hand	Rebar	Cnsmbl	Cnsmbl	Cnsmbl	-
Demo.	11	Smoothing	Grinder	Beam	Exposed Beams	10.00	Beams	Electric Generator
Demo.	12	Smoothing	Grinder	Diaphragm	Exposed Diaphragm Length	39.41	ft	Electric Generator
Demo.	13	Removing	Saw	Strip Seal	Cnsmbl	Cnsmbl	Cnsmbl	Handheld Saw

Appendix B

CONSTRUCTION ACTIONS, DURATIONS, AND RATES

The construction stage of the case-study incurred over a range of 19 days, of which of them were days of work committed to the construction. During the 12 work-days of construction, a total of 232.51 worker-hours were committed to completing the stage. The completion of the construction stage included 56 unique task to component/element operations. The construction stage can be viewed in two periods. A synopsis of the date ranges, days worked, effective worker-hours, and general tasks within each period, all of which will be discussed, can be referred to in Table 71. The first period occurred after the end of the demolition stage and ended after the total dam and parapet base, on the dam side, were constructed with the appropriate reinforcement and formwork, and filled with Class A concrete. The second period began after the first pour, and ended after the wing wall and parapet base on the backwall side, the parapet bodies (on both sides of the dam) were constructed with the appropriate formwork, steel reinforcement and filled with Class A concrete and when the strip seal was fully implemented.

Table 71: Total Durations and Generalized Tasks Associated with the Construction Periods

Period	Date Range (Start)	Date Range (End)	Total Duration in Days	Days Worked	Total Effective Worker-hours	General Tasks
1	5-Aug	17-Aug	19.	7	78.72	Placement of Armoring System
						Placement of Steel Reinforcement in Dam

						Placement of Formwork in Dam and Wing Wall
						Pouring of Concrete in Dam and Parapet Base (Deck)
2	17-Aug	25-Aug	13	7	48.66	Placement of Steel Reinforcement in Parapet Components
						Placement of Wing Wall and Parapet Component Formwork
						Pouring of Concrete in All Parapet Components
						Final Sealant Treatment
						Strip Seal Implementation

The following discussions provided for the two period comprising the construction stage are to provide in the pursuit of supplementing and clarifying the values provided in Tables 72, 73, 74, and 75 that report the durations, rates, order, and descriptions of all tasks and tools witnessed during the construction stage.

Though the lateral length of the dam demolished was 39.41 feet, the length upon which the concrete was to be poured was 36.41 feet. The difference in demolition and pouring lengths were due to the armoring systems that were fabricated for the field and because of the amount of roadway available to be demolished. The armoring systems were fabricated and transported to the site in two pieces for phase 1, that were welded together. It is important to note that the number of segmented armoring systems, that have to be welded together, should be minimized as locations with welds are more vulnerable to fatigue and deterioration than continuous pieces of steel, especially the armoring that is continuously subjected to vehicular impact. Thus, only two pieces of the armoring system could fit within the available area of phase 1 and totaled 36.41 feet, but 39.41 feet of concrete was demolished due to the room available, due to lane closure; thus, the differences in demolition and construction lengths are logical. The distinction between the pouring and demolition length can be clearly seen at the end of the construction stage in Figure 47.

Figure 47: Length Difference Between Pouring and Demolition, the Concrete Held in Place by the "Bulkheads"

B.1 Period 1

The tasks leading up to the end of the first period were done so in the pursuit of pouring Class A concrete into the dam and deck-side parapet base. For the concrete to be poured, the armoring system, steel reinforcement and formwork had to be implemented. Before implementing the armoring system holes had to be drilled into the demolished surface which would eventually be fitted with reinforcement steel bars (or rebars). Rebars that are fitted and epoxied into the concrete, longitudinally, will be referred to as dowels as can be seen in Figure 48. The dowels, anchored into the concrete, will support other types of steel reinforcement that will in turn support the poured concrete. Such reinforcements supported by the dowels are the stirrups (seen in Figure 48) and steel reinforcement bars that run laterally along the length of the demolished length of the dam which will be referred to simply as rebars (seen in Figure 49). The rebars are of the same material and size as the dowels while the stirrups made of the same material as the dowels, are shaped differently as can be seen in Figure 48. Rebars and stirrups are what provides reinforcement to the concrete bridge. Due to concrete's high compressive strength, but relatively low tensile strength the concrete is strengthened in tension with the implementation of such reinforcement. Stirrups are longer and angulated rebars, forming a cage like perimeter, onto which the rebars are tied to, keeping all of the steel reinforcement in place relative to one another while providing another component to resist shear.

Figure 48: Highlighted in Orange is a Dowel Epoxied into the Deck Wall; Highlighted in Yellow is a Stirrup Tied to its Corresponding Dowel.

Figure 49: Highlighted in Blue are the Rebars, that are Visible, Running Laterally Along the Demolition Length of the Dam

The dowels were initially fitted for sizing purposes. The fitting was complimented with sawing and resizing of the dowels to fit properly seen in Figure 50 and 51. A total of 73 holes were drilled into the deck, for the 73 dowels that would be placed and epoxied into the formers' holes. The dowels were placed in two horizontal rows, the top row placed inches below the riding surface and the bottom row above the diaphragm and beams as can be seen in Figure 52. New rebars were introduced only to the deck header and while stirrups were necessary for both sides of the header, the stirrups kept intact on the backwall side were utilized.

Figure 50 Drilling of the holes for the Dowels

Figure 51 Adjusting the Length of the Dowels to Fit the Holes

Figure 52 Placement of the Dowels After the Implementation of the New Armoring System

Figure: 50-52: The drilling of Holes, Adjusting the Rebar Length to Fit, and the Fitting of the Rebars into the Deck

After the holes for the rebars were drilled, and the rebars were fitted for size they had to be removed so that there would be enough room for the armoring system to be placed within the dam reservoir and so that the workers adjust and anchor them to the diaphragm and abutment seat within the deck and backwall headers, respectively. The first armoring system pieces had to be lifted and placed into dam reservoir by the skidder (due to its weight) then adjusted manually. After the first armoring system piece was placed and positioned, the second one was then lifted with the skidder and then manually positioned as can be seen in Figures 53-54. After the armoring systems were positioned, they had to be anchored onto the approach and riding surface to hold the systems in place until they are permanently anchored into the backwall seat and diaphragm, seen in Figure 55.

Figure 53 Placement of the Armoring System in the Dam Via Skidder

Figure 54 Adjustment of the Armoring System in Dam by Hand

Figure: 53-54: The Placement and Adjustment of the Armoring System in the Dam

Figure 55: The Temporary Anchorage of the Armoring Systems onto the Deck and Approach Riding Surfaces

After the armoring system was placed, crew members would intermittently work on constructing the steel reinforcement (rebars) of the wing wall as can be seen in Figure 56. Much of the steel reinforcement was left intact during the demolition process, and they were left in place. Where rebars were missing, or damaged, new ones were implemented by tying them onto the left-in-place reinforcement or by drilling new ones into the side of the untouched surfaced of the wing wall. In total, 6 rebars were drilled and epoxied into the depth of the wing wall (vertically), 2 were drilled and epoxied, longitudinally, into the existing wing wall (horizontally), and 8 horizontal rebars were tied to the existing and newly drilled vertical rebars. Thus, for the wing wall, 16 rebars were implemented, in varying arrangements.

Figure 56: The Intermittent Placement of the Wing Wall/ Backwall Sided Parapet Base Steel Reinforcement

Formwork was then constructed for the deck and backwall. The formwork on the backwall side consisted of wood and cork while the formwork on the deck side of the header consisted of sheet metal. The wooden formwork, seen in Figures 57-58, was nailed into the abutment wall from the catwalk underneath the superstructure and extended to the upper lip of the armoring. The wooden formwork, running laterally along the armoring system to the bulkhead, would impede the newly poured concrete in the dam from seeping from the backwall into the abutment seat, which would ultimately drain the backwall of all its concrete.

Figure 57
The Wooden Fromwork Being Nailed into the Abutment, Underneath the Bridge from the Catwalk

Figure 58
Note the Wooden Formwork
Between the Armoring

Figure: 57-58: The Implementation of the Wooden Formwork for the Backwall Along the Length of the Dam to be Poured on

The metal formwork, being that the deck header was demolished at a width of 2.5 feet from the joint reservoir, needed barriers to contain and hold the concrete from the bottom and side of the reservoir not contained by the superstructure and deck pan, as can be seen in Figure 59. The metal formwork and wooden formwork were constructed simultaneously. Thus angulated sheet metal had to be cut, and fitted to extend from the diaphragm to the bottom lip of the armoring where they would be welded.

Figure 59: The Metal Formwork Running Along the Pouring Length of the Dam, Connected to the Diaphragm and Bottom Lip of the Armoring

Once the steel, and wooden formwork were constructed, the motor driven welder was delivered to the site. The anchorage on the deck header side of the dam was to be welded to the diaphragm (5 in total) while backwall side anchorage systems were to be drilled and epoxied into the abutment seat (as no metallic surfaces were present, 10 in total). First, the two armoring system pieces were welded to one another. The metal formwork was then welded along the edges of the diaphragm to metal formwork interfaces and along the edge of the metal formwork to the bottom lip interface. Figure 60 shows the armoring pieces being welded to one another.

Figure 60: Welding of the Two Separately Delivered and Implemented Armoring Systems to One Another

As the welding took place, the abutment seat anchorage systems were drilled, filled with grout as an adhesive, then fitted with the anchorage component of the armoring system as can be seen in Figures 61-63. After the welding took place, it was then possible to epoxy and fit the dowels in the deck, implement the stirrups, and ties all in between the bulkheads.

Figure 61 Drilling of the Anchorage Holes in the Backwall

Figure 62 Pouring of Grout in the Anchorage Holes

Figure 63 Placement of the Anchorage Component into the Holes with Grout

Figure: 61-63: The Drilling, Pouring of Grout, and Application of the Anchorage Component for the Backwall Anchorage System

After the dowels were drilled and epoxied into the deck, a stirrup was tied to each top dowel; in some cases, a stirrup was not provided due to geometric constraints within the deck header. Afterwards, the rebars were placed within within the cage like perimeter, between the first and second row of the epoxied dowels, encased within the sitrrups. Figure 64 shows the workers placing and tying all steel reinforcement within the deck header. It was assumed that 13 individual pieces of rebar, of 36.41 feet each, were used while 73 dowel pieces were inserted and epoxied into the deck, 38 in the top row, and 35 in the bottom row with each piece being 2.92 feet long. A total of 33 stirrups were tied to the top row of dowels. Before providing the steel reinforcement on the backwall, formwork had to be implemented between the backwall and approach components.

Figure 64: Implementation of the Stirrups and Rebars Through Tying

The cork formwork was placed laterally along the interface surface between the demolished backwall and the approach within the demolished reservoir of the backwall, as seen in Figure 65, completed after the placement of the rebars so as not to impede the placement process. The backwall and approach are two separate components that are also allowed to expand and contract. The cork serves as a divider between the newly formed concrete and the abutment riding surface to allow for slight movement between the two components. In the second period of construction, the cork would ultimately be grinded down to a certain depth below the concrete riding surface then filled with silicone, forming a minute joint sealant, also running longitudinally from the parapet to the bulkhead of the dam. For the backwall steel reinforcement, the same procedures were followed on the backwall side except that it was assumed that 4 individual rebar pieces that ran laterally from the parapet to where to bulkhead would be implemented, also seen in Figure 65.

Figure 65: The Cork Formwork Can Be Seen Along the Backwall-Approach Riding Surface Interface, Parallel to the Newly Implemented Rebars

Both sides of the dam consisted of bulkheads, made of wood. Both the deck and backwall consisted of bulkheads serving as a barrier that would impeded what would be the newly poured concrete from seeping out of the demolished volume. A bulkhead was then provided at the parapet fascia (the side of the parapet on the outermost southern edge of the parapet surface, facing the railroad) on the deck header side of the parapet base, as the deck header sided parapet base was to be filled along with the dam. Another bulkhead was provided at the interface of the backwall sided parapet base that would impede the newly poured concrete in the dam from seeping into the aforementioned base and wing wall, both of which would be poured at two separate times, in the second period. The bulkheads of the deck and backwall facing the opposing direction of traffic can be seen in Figure 47.

With the formwork set up and the steel reinforcement implemented, it was time to pour the concrete. Before curing could begin an adhesive was sprayed onto the surfaces of the void so that the concrete to facilitate adhesion between the new concrete and all of the components that was to come into contact with it seen in Figure 66. A concrete truck arrived on the site and pouring began as seen in Figure 67. As seen in the image, the pouring of the concrete was assisted by a worker with a shovel, and to facilitate the dissemination of the viscous liquid within the voids and steel reinforcement, a concrete vibrator, a power driven, hose-like apparatus, was inserted into the concrete, assisting in the consolidation of the freshly poured concrete. After the concrete was poured, workers were assigned to smoothing the liquid and sprayed it with a curing compound as seen in Figure 68. After spraying the curing compound wet burlap, a weeper hose (to keep the burlap and concrete surface moist, connected to an on-site water tank), and tarp were all placed on top of the concrete, in the aforesaid order, to assist in the curing of the concrete as seen in Figures 69-71.

Figure 66
Spraying of the Adhesive Spray

Figure 67
Pouring of the Concrete from the Truck, assisted with a Worker with a Shovel, with a Mechanical Vibrator Placed Within the Newly Poured Concrete to Facilitate Dissemination of the Concrete

Figure: 66-67: Preparing the Headers Before Pouring of the Concrete and During the Pouring

Figure 68: The Smoothing of the Newly Poured Concrete Paired with the Spraying of the Curing Compound

Figure 69
On-Site Water Tank

Figure 70
Placement of the Moist Burlap and Weeper Hose

Figure 71
Placement of the Plastic Tarp atop of the Wet Burlap and Weeper Hose

Figure: 69-71: Placement of the Wet Burlap, Weeper Hose, and Plastic Tarp atop of the Newly Poured Concrete to Assist in Curing

All task descriptions, durations, dependencies and rates of the first period have bene included in Table 72, with information regarding the values upon which the values were determined in Table 73. It is important that such values are tabulated so that the reader can become more familiar with the tasks incurred on the field, and because such values are vital in determining the material, fuel, and pollutant costs associated with the tasks observed on Edgemoor Road, and importantly, for the simulation of other joint replacements.

Table 72: Task Description Durations and Rate from the Construction Stage Onset to the End of the First Pour

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Duration (Worker-hours)	Rate	Unit
Const.	18	Drilling	Drill	-	Rebar	Deck	17(C)	7.33	9.95	Unt/WHr
Const.	19	Sawing	Grinder	Rebar	-	Deck	18(C)	2.08	35.04	Unt/WHr
Const.	20	Positioning	Skidder	-	Armoring System	Dam	19(C)	0.37	Cnsmbl	Cnsmbl
Const.	21	Positioning	By Hand	-	Armoring System	Dam	20(C)	4.13	Cnsmbl	Cnsmbl
Const.	22	Positioning	Skidder	-	Armoring System	Dam	21(C)	0.20	Cnsmbl	Cnsmbl
Const.	23	Positioning	By Hand	-	Armoring System	Dam	22(C)	0.83	Cnsmbl	Cnsmbl
Const.	24	Sawing/ Smoothing	Grinder	Armoring Connection	-	Dam	23(C)	1.37	8.03	Unt/WHr
Const.	25	Drilling	Drill	-	Armoring System Support	Dam	22(C)	0.37	Cnsmbl	Cnsmbl
Const.	26	Removing	By Hand	-	Anchorage	Dam	25(C)	0.50	30.00	Unt/WHr
Const.	27	Drilling	Drill	Anchorage	Abutment Seat	Backwall	26(C)	1.98	10.08	Unt/WHr
Const.	28	Sawing	Saw	Wood	Formwork	Backwall	23(C)	1.33	27.31	LF/WHr
Const.	29	Sawing	Grinder	Metal	Formwork	Deck	23(C)	8.77	4.15	LF/WHr
Const.	30	Drilling	Drill	-	Rebar	Wing Wall	23(C)	0.63	12.63	Unt/WHr
Const.	31	Placing	By Hand	Wood	Formwork	Backwall/ Dam	28(C)	5.15	7.07	LF/WHr
Const.	32	Sawing	Saw	Kicker	-	Dam	24(C)	0.12	Cnsmbl	Cnsmbl
Const.	33	Placing	By Hand	Kicker	Armoring	Dam	32(C)	0.10	Cnsmbl	Cnsmbl
Const.	34	Placing	Saw	Wood	Formwork (Blockout)	Parapet Base (Deck)	17(C)	3.93	Cnsmbl	Cnsmbl
Const.	35	Tack Welding	Engine Driven Welder	Welding Stick Electrodes	Metal Formwork+ Armoring+ Anchorage (Deck)	Dam	29(C)	1.53	34.62	LF/WHr
Const.	36	Placing	By Hand	Anchorage	Abutment Seat	Backwall	27(C)	1.50	6.67	Unt/WHr
Const.	37	Placing	By Hand	Rebar+Stirrups	-	Deck	29(C)	16.12	2.45	LF/WHr
Const.	38	Repositioning	By Hand	Bracket	-	Backwall	-	0.62	Cnsmbl	Cnsmbl
Const.	39	Placing	By Hand	Rebar	-	Backwall	27(C)	4.70	8.39	LF/WHr
Const.	40	Placing	By Hand	Rebar	-	Wing Wall	30(C)	2.90	5.52	Unt/WHr
Const.	41	Placing	Drill	Wood	Formwork	Parapet Base (Bw)	40(C)	3.00	Cnsmbl	Cnsmbl
Const.	42	Placing	By Hand	Cork	Formwork	Backwall	39(C)	1.67	21.85	LF/WHr

Const.	43	Placing	Saw	Wood	Formwork (Blockout)	Backwall	42(C)	0.33	Cnsmbl	Cnsmbl
Const.	44	Placing	Saw	Wood	Formwork (Blockout)	Deck	37(C)	1.42	Cnsmbl	Cnsmbl
Const.	45	Spraying	By Hand	Concrete Adhesive	-	Dam and Pp Base (Deck)	44(C)	0.10	1316.85	SF/WHr
Const.	46	Pouring	Concrete Truck	Wet Concrete	-	Dam and Pp Base (Deck)	45(C)	0.57	204.64	CF/WHr
Const.	47	Shoveling	By Hand	Wet Concrete	-	Dam and Pp Base (Deck)	46(I)	1.13	102.32	CF/WHr
Const.	48	Vibrating	Vibrator	-	Wet Concrete	Dam and Pp Base (Deck)	46(I)	0.57	204.64	CF/WHr
Const.	49	Smoothing	By Hand	-	Wet Concrete	Dam and Pp Base (Deck)	48(C)	2.90	45.41	SF/WHr
Const.	50	Spraying	By Hand	Curing Compound	Wet Concrete	Dam and Pp Base (Deck)	49(C)	0.07	1975.27	SF/WHr
Const.	51	Placing	By Hand	Burlap	Wet Concrete	Dam and Pp Base (Deck)	51(C)	0.27	143.75	LF/WHr
Const.	52	Placing	By Hand	Weeper Hose	Wet Concrete	Dam and Pp Base (Deck)	51(C)	0.07	575.00	LF/WHr
Const.	53	Placing	By Hand	Tarp	Wet Concrete	Dam and Pp Base (Deck)	52(C)	0.07	575.00	LF/WHr

Table 73: Rate Dependency Descriptions, Values and Power Sources of Tasks from Initiation of the Stage to the End of the First Pour

Stage	Index	Tool	Applicant	Component's Element	Rate Dependence	Rate Dependent Value	Unit	Power Source
Const.	18	Drill	-	Rebar	Dowels	73.00	Rebar	Electric Generator
Const.	19	Grinder	Rebar	-	Dowels	73.00	Rebar	Electric Generator
Const.	20	Skidder	-	Armoring System	Cnsmbl	Cnsmbl	Cnsmbl	Skidder
Const.	21	By Hand	-	Armoring System	Cnsmbl	Cnsmbl	Cnsmbl	-
Const.	22	Skidder	-	Armoring System	Cnsmbl	Cnsmbl	Cnsmbl	Skidder
Const.	23	By Hand	-	Armoring System	Cnsmbl	Cnsmbl	Cnsmbl	-
Const.	24	Grinder	Armoring Connection	-	Armoring Attachments	11.00	Attachments	Electric Generator
Const.	25	Drill	-	Armoring System Support	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	26	By Hand	-	Anchorage	Brackets	15.00	Brackets	-
Const.	27	Drill	Anchorage	Abutment Seat	Anchrg Holes	20.00	Holes	Electric Generator
Const.	28	Saw	Wood	Formwork	Const+Pp Length	36.41	ft	Saw
Const.	29	Grinder	Metal	Formwork	Pouring Length	36.41	ft	Electric Generator
Const.	30	Drill	-	Rebar	Wing Wall Holes	8.00	Holes	Electric Generator
Const.	31	By Hand	Wood	Formwork	Pouring Length	36.41	ft	-
Const.	32	Saw	Kicker	-	Cnsmbl	Cnsmbl	Cnsmbl	Saw
Const.	33	By Hand	Kicker	Armoring	Cnsmbl	Cnsmbl	Cnsmbl	-
Const.	34	Saw	Wood	Formwork (Blockout)	Cnsmbl	Cnsmbl	Cnsmbl	Saw
Const.	35	Engine Driven Welder	Welding Stick Electrodes	Metal Formwork+ Armoring+ Anchorage (Deck)	Length of Metal Formwork+ Armoring+ Anchorage (Deck)	53.08	ft	Engine Driven Welder
Const.	36	By Hand	Anchorage	Abutment Seat	Brackets	10.00	Brackets	-
Const.	37	By Hand	Rebar+Stirrups	-	Const. Length	39.41	ft	-
Const.	38	By Hand	Bracket	-	Cnsmbl	Cnsmbl	Cnsmbl	-

Const.	39	By Hand	Rebar	-	Const. Length	39.41	ft	-
Const.	40	By Hand	Rebar	-	Dowels	16.00	Holes	0.00
Const.	41	Drill	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	42	By Hand	Cork	Formwork	Pouring Length	36.41	ft	-
Const.	43	Saw	Wood	Formwork (Blockout)	Cnsmbl	Cnsmbl	Cnsmbl	Saw
Const.	44	Saw	Wood	Formwork (Blockout)	Cnsmbl	Cnsmbl	Cnsmbl	Saw
Const.	45	By Hand	Concrete Adhesive	-	Total Dam and Pp Base (Deck) Surface Area	131.68	ft^2	-
Const.	46	Concrete Truck	Wet Concrete	-	Total Dam and Pp Base (Deck) Volume	115.96	ft^3	Concrete Truck
Const.	47	By Hand	Wet Concrete	-	Total Dam and Pp Base (Deck) Volume	115.96	ft^3	-
Const.	48	Vibrator	-	Wet Concrete	Total Dam and Pp Base (Deck) Volume	115.96	ft^3	Electric Generator
Const.	49	By Hand	-	Wet Concrete	Total Dam and Pp Base (Deck) Surface Area	131.68	ft^2	-
Const.	50	By Hand	Curing Compound	Wet Concrete	Total Dam and Pp Base (Deck) Surface Area	131.68	ft^2	-
Const.	51	By Hand	Burlap	Wet Concrete	Dam and Pp (Deck) Length	38.33	ft	-
Const.	52	By Hand	Weeper Hose	Wet Concrete	Dam and Pp (Deck) Length	38.33	ft	-
Const.	53	By Hand	Tarp	Wet Concrete	Dam and Pp (Deck) Length	38.33	ft	-

B.2 Period 2

The second period of the construction stage can be generalized as the segment of the construction stage that is fully committed to preparing the parapets to be constructed, and to implement the strip seal joint in the newly formed armoring. During the second period, two separate occurrences of concrete pouring occurred, once for the wing wall and base of the parapet on the backwall side of the dam, and secondly to fill the parapet body on both sides of the dam.

Before the formwork of the wing wall and parapet base could be constructed, the steel reinforcement in the parapet bodies, on both sides of the dam, had to be implemented. The dowels were kept intact from the demolition stage and were used without the addition of any other reinforcement, except for the stirrups that can be seen in Figure 72. A total of 8 and 6 stirrups were implemented on the parapet bodies on the backwall and deck sides of the headers, respectively. The stirrups were arranged in a manner that each sequential stirrup was rotated 180 degrees from the one before it.

To prepare the wing wall and parapet body for second pour, wood was sawed, drilled, and placed to provide the formwork so that the concrete poured in the wing wall and base while being contained as can be seen in Figure 72.


Figure 72: Formwork of the Wing Wall and Parapet Base

After the formwork was developed the wing wall and base were prepped with sprayed adhesive pre-pouring, then subjected to shoveling and vibrating of the concrete during the pouring, then the smoothing, spraying of the curing compound, wet burlap, weeping hose and tarp, to assist in the curing process, post concrete. procedurally in the same manner as for the dam as can be seen in Figure 73.

Figure 73: Filling of the Wing Wall and Parapet Base with Concrete

To prepare the parapet body, on both sides of the dam, the same procedures observed in the pouring of the dam and deck sided parapet base, and the wing wall and backwall sides base, in developing the formwork, pouring, and curing were followed as can be seen in Figure 74. The formwork for the parapet body was provided through a combination of carpentry and an older pre-formed steel piece that was made to conform to the curvature and angulations of the parapet body seen in Figure 74. Afterwards, the parapet bodies were subjected to the same pre-pouring, pouring, then curing techniques observed in the other two pours that occurred.

Figure 74: Formwork of the Parapet Bodies

After the concrete had been cured and hardened, the silicone sealant between the backwall and the roadway approach had to be provided. The implemented cork between the two entities, was grinded down below the riding surface so that the eventual reservoir could be filled with the silicone sealant. After the cork was grinded, primer was brushed onto the concrete surface to facilitate adhesion between the cork and the new sealant seen in Figure 75. Immediately after the concrete was cured and hardened, the strip sealant was applied to the armoring that included pockets within which the sealant could be inserted and attached through the use of adhesives as seen in Figure 76.

Figure 75: Application of Silicone Within the Backwall and Approach Riding Surface Interface, Above the Cork Formwork

Figure 76: Implementation of the Strip Seal Extrusion into the Armoring

The total concrete pouring and partial reconstruction occurred from the parapet fascia through the eastbound direction roadway to its interface with the median. The newly formed dam and parapet can be seen in Figure 77.

Figure 77: Depiction of Replaced Headers of Lane 1 and the Parapet Resulting from Completion of the Case-Study

All of the descriptions, durations, dependencies and rates of the second period have bene included in Table 74, with information regarding the values upon which the values were determined in Table 75.

Table 74: The Tasks Incurred After the First Pouring of the Dam and Parapet Base Ending at the End of the Case-Study

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Duration (Worker-hours)	Rate	Unit
Const.	54.00	Placing	By Hand	Stirrups	-	Parapet Body	40(C)	4.23	3.31	Unt/WHr
Const.	55.00	Placing	Drill	Wood	Formwork	Wing Wall Fascia	54(C)	4.50	Cnsmbl	Cnsmbl
Const.	56.00	Placing	Drill	Wood	Formwork	Parapet Base Fascia	55(I)	2.00	Cnsmbl	Cnsmbl
Const.	57.00	Spraying	By Hand	Concrete Adhesive	-	Wing Wall/ Parapet Base (Bw)	56(C)	0.03	201.79	SF/WHr
Const.	58.00	Pouring	Concrete Truck	Wet Concrete	-	Wing Wall/ Parapet Base (Bw)	57(C)	0.23	50.88	CF/WHr
Const.	59.00	Vibrating	Vibrator	Wet Concrete	-	Wing Wall/ Parapet Base (Bw)	58(C)	0.35	33.92	CF/WHr
Const.	60.00	Smoothing	By Hand	-	Wet Concrete	Wing Wall/ Parapet Base (Bw)	59(C)	0.30	22.42	SF/WHr
Const.	61.00	Spraying	By Hand	Curing Compound	Wet Concrete	Wing Wall/ Parapet Base (Bw)	60(C)	0.02	403.59	SF/WHr
Const.	62.00	Placing	By Hand	Burlap	Wet Concrete	Wing Wall/ Parapet Base (Bw)	61(C)	0.03	201.79	SF/WHr
Const.	63.00	Placing	Drill/ Saw	Wood	Formwork	Parapet Body	54(C)	15.10	Cnsmbl	Cnsmbl
Const.	64.00	Spraying	By Hand	Insulating Foam Sealant	Formwork	Parapet Body	63(C)	0.25	158.91	SF/WHr
Const.	65.00	Spraying	By Hand	Concrete Adhesive	-	Parapet Body	64(C)	0.02	658.23	SF/WHr
Const.	66.00	Pouring	Concrete Truck	Wet Concrete	-	Parapet Body	65(C)	0.33	65.41	CF/WHr
Const.	67.00	Shoveling	By Hand	Wet Concrete	-	Parapet Body	66(C)	0.33	65.41	CF/WHr
Const.	68.00	Vibrating	Vibrator	-	Wet Concrete	Parapet Body	67(C)	0.33	65.41	CF/WHr
Const.	69.00	Smoothing	By Hand	-	Wet Concrete	Parapet Body	68(C)	0.42	14.48	SF/WHr

Const.	70.00	Spraying	By Hand	Curing Compound	Wet Concrete	Parapet Body	69(C)	0.03	181.01	SF/WHr
Const.	71.00	Grinding	Grinder	Cork	Formwork	Backwall	53(C)	0.20	182.06	LF/WHr
Const.	72.00	Applying	By Hand	Primer	Cork	Backwall	71(C)	0.05	728.23	LF/WHr
Const.	73.00	Pouring	AT 1200 S	Silicone	-	Backwall	72(C)	0.15	242.74	LF/WHr
Const.	74.00	Applying	By Hand	Methacrylate	-	Backwall	73(C)	0.08	450.05	LF/WHr
Const.	75.00	Placing	By Hand	Strip Seal Extrusion	Armoring	Dam	53(C)+CrngTim	19.67	1.85	LF/WHr

Table 75: Rate Dependency Descriptions, Values and Power Sources for all Construction Tasks After the First Pour to the End of the Case-Study

Stage	Index	Task	Tool	Applicant	Component's Element	Rate Dependence	Rate Dependent Value	Unit	Power Source
Const.	54.00	Placing	By Hand	Stirrups	-	Stirrups	14.00	Stirrupts	-
Const.	55.00	Placing	Drill	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	56.00	Placing	Drill	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	57.00	Spraying	By Hand	Concrete Adhesive	-	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	58.00	Pouring	Concrete Truck	Wet Concrete	-	Wing Wall/ Parapet Base(Bw) Volume	11.87	ft^3	Concrete Truck
Const.	59.00	Vibrating	Vibrator	Wet Concrete	-	Wing Wall/ Parapet Base(Bw) Volume	11.87	ft^3	Electric Generator
Const.	60.00	Smoothing	By Hand	-	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	61.00	Spraying	By Hand	Curing Compound	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	62.00	Placing	By Hand	Burlap	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	63.00	Placing	Drill/ Saw	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator

Const.	64.00	Spraying	By Hand	Insulating Foam Sealant	Formwork	Total Parapet Body Area Encasement	39.73	ft^2	-
Const.	65.00	Spraying	By Hand	Concrete Adhesive	-	Total Parapet Body Surface Area of Bases	10.97	ft^2	-
Const.	66.00	Pouring	Concrete Truck	Wet Concrete	-	Total Parapet Body Volume	21.80	ft^3	Concrete Truck
Const.	67.00	Shoveling	By Hand	Wet Concrete	-	Total Parapet Body Volume	21.80	ft^3	-
Const.	68.00	Vibrating	Vibrator	-	Wet Concrete	Total Parapet Body Volume	21.80	ft^3	Electric Generator
Const.	69.00	Smoothing	By Hand	-	Wet Concrete	Total Parapet Body Top Surface Area (Top)	6.03	ft^2	-
Const.	70.00	Spraying	By Hand	Curing Compound	Wet Concrete	Total Parapet Body Top Surface Area (Top)	6.03	ft^2	-
Const.	71.00	Grinding	Grinder	Cork	Formwork	Pouring Length	36.41	ft	Electric Generator
Const.	72.00	Applying	By Hand	Primer	Cork	Pouring Length	36.41	ft	-
Const.	73.00	Pouring	AT 1200 S	Silicone	-	Pouring Length	36.41	ft	Air Compressor
Const.	74.00	Applying	By Hand	Methacrylate	-	Pouring Length	36.41	ft	Air Compressor
Const.	75.00	Placing	By Hand	Strip Seal Extrusion	Armoring	Pouring Length	36.41	ft	-

Appendix C

Cleaning Actions, Durations, and Rates

Cleaning was usually considered to be applied to the whole of the dam since airblasting and sandblasting were not endeavors specifically applied to one side of the dam and because such treatments would ultimately effect the dam as a whole. Thus, airblasting and sandblasting were considered to be tasks associated with the dam. Airblasting occurred throughout the duration of the demolition stage (seen in Figure 78) to remove debris buildup in the dam reservoir, enabling workers to continue their demolition tasks while providing a better view of what they were demolishing and how much progress they were making. Sandblasting occurred intermittently during the end of the demolition stage (seen in Figure 79) and at the end of the phase. Sandblasting was employed to abrasively clean the concrete surfaces from foreign debris so as to provide a clean and smooth, in-place concrete surface so that newly poured concrete and adhesives applied in the construction stage could adhere to the existing concrete. At the end of a phase, before opening the roadways, sandblasting and airblasting were employed to clean the entire roadway and the newly constructed components of the bridge in order to rid the surfaces of dust and rubble for the incoming traffic. Other cleaning treatments that were applied to the backwall, deck, or parapet, such as the smoothing of excess concrete on the parapet body facing the roadway and on the Parapet Base and Wing Wall fascia (seen in Figures 80 and 81), were recorded as tasks pertaining to that specific component of the bridge.

Airblasting occurred for 3.34 hours; of the 3.33 hours of airblasting, 2.32 hours of airblasting occurred intermittently between demolition tasks and 1.02 hours of airblasting occurred at the end of phase 1, complimented with sandblasting, to clean the bridge deck of debris. Sandblasting occurred for 1.72 hours of which .97 hours of the total sandblasting duration occurred intermittently during the end of the demolition stage and .75 of constant airblasting occurred at the end of phase 1, along with airblasting, for a final cleaning of the deck.

Figure 78: An Example of One of the Many Intermittent Airblasting Session at the End of the First Day of the Demolition Stage

Figure 79: An Example of an Intermittent Sandblasting Session in the Dam In-Between 79he Placement of the Rebars in the Deck and Backwall Headers

Figure 80 Grinding of Cured Concrete on Roadway Parapet Face

Figure 81 Grinding of Cured Concrete on Parapet Base Fascia

Figure: 80-81: Smoothing of Newly Formed Concrete for Roadway Parapet Barrier Face and Parapet Base Fascia

The following tasks were observed in the relative order tabulated below in Table 76. A faux index was provided for record keeping sake and to provide the relative order of all cleaning tasks, as they often occurred randomly. The idling time observed from the skidder was recorded as a task due to the fact that it was the third most used motor on the field, third to the air compressor and electric generator.

Table 76 represents a list of unique tasks performed on the bridge in the pursuit of cleaning with their associated bridge components, components' elements, index dependencies, durations and ultimately the rates. Tasks such as cleaning rubble by hand from the dam and cleaning rubble by hand from the parapet initially seem like two tasks that could be combined (Faux indices A and F, respectively), summing their volumes and durations and determining the rate; however, upon further inspection the seemingly similar tasks when applied to the dam and when applied to the parapets the rates differ by 27.6 CF/WHr. The much larger rate associated with the rubble collection within the dam is possibly due to accessibility. Table 77 consists of reference cells so that the reader can develop and understanding as to how such rates were developed while keeping in mind the power sources utilized which will be discussed in the upcoming sections.

Table 76: Task Descriptions, Durations, and Rates of Cleaning Tasks Spanning the Demolition and Construction Stages of the Case-Study

Stage	Faux Index	Task	Tool	Component's Element	Bridge Component	Index Dependence	Duration	Rate	Unit
Cg.	A	Airblasting	Airblaster	Debris	Dam	3(I)	2.32	68.53	CF/WHr
Cg.	B	Collecting	By Hand	Rubble	Dam	3(I)	28.27	5.62	CF/WHr
Cg.	C	Collecting	Skidder	Rubble	Dam	3(I)	5.03	31.56	CF/WHr
Cg.	D	Sandblasting	Sandblaster	Rubble	Dam	6(C)	0.97	164.23	CF/WHr
Cg.	E	Collecting	By Hand	Rubble	Parapet Body	6(C)	0.67	Cnsmbl	Cnsmbl
Cg.	F	Vacuuming	Vacuum	Drilled Hole Debris	Backwall	27(C)	0.50	40.00	Unt/WHr
Cg.	G	Smoothing	Grinder	Concrete	Dam	53(C)	1.58	80.49	SF/WHr
Cg.	H	Smoothing	Grinder	Concrete	Parapet Body	70(C)	2.25	17.66	SF/WHr
Cg.	I	Sandblasting	Sandblaster	Rubble	All	74(C)	0.75	Cnsmbl	Cnsmbl
Cg.	J	Airblasting	Airblaster	Debris	All	74(C)	1.02	Cnsmbl	Cnsmbl

Table 77: Rate Dependency Descriptions, Values and Power Sources Associated with all Cleaning Tasks

Stage	Faux Index	Task	Tool	Component's Element	Rate Dependence	Rate Dependent Value	Unit	Power Source
Cg.	A	Airblasting	Airblaster	Debris	Total Volume Demolished	158.75	ft^3	Air Compressor
Cg.	B	Collecting	By Hand	Rubble	Total Volume Demolished	158.75	ft^3	-
Cg.	C	Collecting	Skidder	Rubble	Total Volume Demolished	158.75	ft^3	Skidder
Cg.	D	Sandblasting	Sandblaster	Rubble	Total Volume Demolished	158.75	ft^3	Air Compressor
Cg.	E	Collecting	By Hand	Rubble	Cnsmbl	Cnsmbl	Cnsmbl	-
Cg.	F	Vacuuming	Vacuum	Drilled Hole Debris	Anchrg Holes	20.00	Holes	Electric Generator
Cg.	G	Smoothing	Grinder	Concrete	Dam Surface Area	127.44	ft^2	Electric Generator
Cg.	H	Smoothing	Grinder	Concrete	Parapet Body Surface Area	39.73	ft^2	Electric Generator
Cg.	I	Sandblasting	Sandblaster	Rubble	Cnsmbl	Cnsmbl	Cnsmbl	Air Compressor
Cg.	J	Airblasting	Airblaster	Debris	Cnsmbl	Cnsmbl	Cnsmbl	Air Compressor

Appendix D

OWNER COSTING FACTORS AND RESULTS OF CASE STUDY

D.1 Wage Rates and Costs

According to the State of Delaware: Department of Labor Division of Industrial Affair: Office of Labor Law Enforcement, the wage rates provided in Table 78, relevant to what was seen on the field, are paid in New Castle County, Delaware, for construction work.

Table 78: Labor Types and Wages in New Castle County for Construction Related Occupations ("Prevailing Wages for Highway Construction," 2014)

County	New Castle
Classification	Wages ($/hr)
Bricklayers	48.08
Carpenters	43.15
Cement Finishers	30.88
Electrical Line Workers	22.5
Electricians	62.1
Iron Workers	42.2
Laborers	33.01
Millwrights	16.11
Painters	60.64
Piledrivers	66.42
Power Equipment Operators	41.18
Sheet Metal Workers	22.75
Truck Drivers	33.9

With the following wage rates and the known number of workers, what type of worker that were considered to be laborers, heavy equipment operators, carpenters, and foremen and how long each worker was charging their wages to the Edgemoor Road Southern abutment joint replacement. Table 79 provides the total number worker-hours spent by each worker type, and the associated wages incurred to the owner to pay each worker-type. Figure 80 provides the wages paid by the contractor to its employees on a daily basis during the completion of the job.

Table 79: Total Workers on the Field, and the Corresponding Man-Hour Durations and Wages on a Daily Basis

Date	Billable Durations per Worker-Type (Man-Hours)					Wages Billed to Contractor ($)					Total Wages per Day ($)
	Oversight(f)	l	ca	p	w	Oversight(f)	l	ca	p	w	
7/30	7	14	0	0	0	302.05	462.14	0.00	0.00	0.00	764.19
7/31	7	23	0	5	0	302.05	767.48	0.00	156.80	0.00	1226.33
8/3	7	35	0	0	0	302.05	1155.35	0.00	0.00	0.00	1457.40
8/4	7	28	0	0	0	302.05	924.28	0.00	0.00	0.00	1226.33
8/5	7	42	0	0	0	302.05	1386.42	0.00	0.00	0.00	1688.47
8/6	7	26	0	2	0	302.05	843.41	0.00	80.87	0.00	1226.33
8/7	7	34	0	1	0	302.05	1117.39	0.00	37.96	0.00	1457.40
8/10	7	42	0	0	0	302.05	1379.82	0.00	6.60	0.00	1688.47
8/13	12	21	0	0	2	537.94	693.21	0.00	0.00	66.16	1297.31
8/14	7	28	7	0	0	302.05	924.28	302.05	0.00	0.00	1528.38
8/17	7	21	7	0	0	302.05	693.21	302.05	0.00	0.00	1297.31
8/18	7	11.0	0	1	0	302.05	363.14	0.00	16.51	0.00	681.70
8/19	4.5	17.6	0	0	0	194.18	580.43	0.00	13.75	0.00	788.36
8/20	5.3	15.8	0	0	0	226.54	519.91	0.00	0.00	0.00	746.45
8/21	7	13.0	0	3	0	302.05	428.58	0.00	91.33	0.00	821.96
8/24	9	28.5	0	2	0	388.35	941.34	0.00	68.77	0.00	1398.46
8/25	2.3	4.6	2.3	0.00	0.00	99.25	151.85	99.25	0.00	0.00	350.34

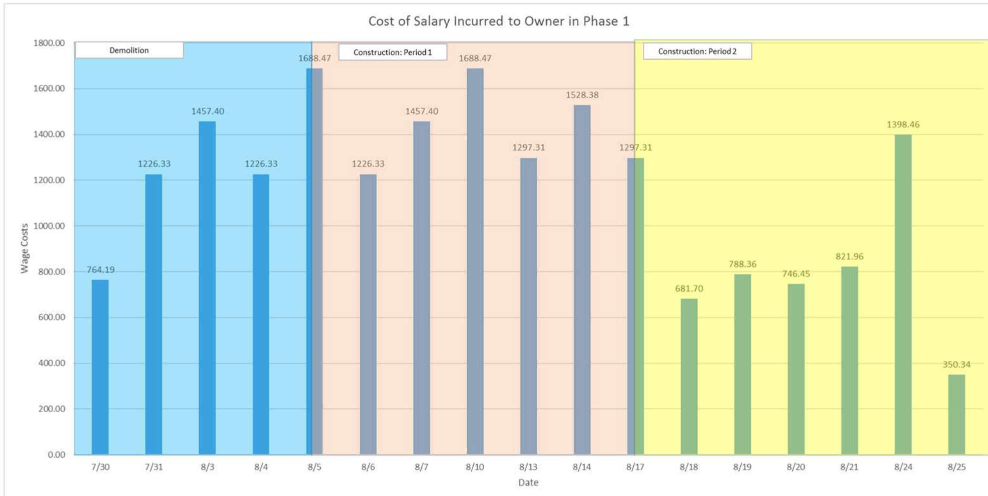

Figure 82: Fluctuation of Wages Paid by Contractor on a Daily Basis Throughout of All Stages and Stage Periods

Table 80: Daily Efficiency Measurements Based on Billable Hours During the Case-Study

Date	Supervision(f)	f	l	ca	p	w	Total Effective Durations (WHr)	Idling Duration (WHr)	Efficiency
7/30	7.00	0.00	9.45	0.00	0.00	0.00	17.25	3.75	82.14
7/31	7.00	1.63	13.80	0.00	4.48	0.00	25.28	9.72	72.24
8/3	7.00	0.00	15.38	0.00	0.00	0.00	22.38	19.62	53.29
8/4	7.00	0.67	12.72	0.00	0.00	0.00	19.72	15.28	56.33
8/5	7.00	0.48	31.68	0.00	0.00	0.00	38.68	10.32	78.95
8/6	7.00	0.53	9.77	0.00	1.68	0.00	18.45	16.55	52.71
8/7	7.00	0.20	10.45	0.00	1.03	0.00	18.48	23.52	44.01
8/10	7.00	0.00	12.40	0.00	0.20	0.00	19.60	29.40	40.00
8/13	12.47	0.00	13.00	0.00	0.00	1.53	27.00	8.00	77.14
8/14	7.00	0.00	14.32	5.37	0.00	0.00	26.68	15.32	63.53
8/17	7.00	0.00	9.70	4.62	0.00	0.00	21.88	13.12	62.52
8/18	7.00	0.00	4.50	0.00	0.50	0.00	12.00	6.50	64.86
8/19	4.50	0.00	9.03	0.00	0.42	0.00	14.17	8.33	62.96
8/20	5.25	0.00	15.10	0.00	0.00	0.00	20.35	0.65	96.90
8/21	7.00	0.00	3.80	0.00	1.43	0.00	12.57	10.18	55.24
8/24	9.00	0.00	19.77	0.00	0.33	0.00	29.10	10.50	73.48
8/25	2.30	0.00	1.83	1.83	0.00	0.00	5.97	3.23	64.86

The carpenter and skidder operator were similar in their efficiency which was, on average, 71.46%. The laborers, however, had an efficiency of 51.18%, or 20.28% less than the average efficiency of the carpenter and skidder operator, shown in Table 81. It should be noted that such a large difference in efficiencies can be due to the fact that the tasks the laborers had to complete were the most physically demanding in comparison to the skidder operator, who sat in an air conditioned cabin, and the carpenter, who spent much of his time constructing the parapets therefore staying in one location working on more skilled than physical labor near the fascia of the bridge where there was more shade.

Table 81: Total Durations and Efficiency per Worker-Type

Worker-Type	Effective Duration (Hours)	Duration Towards Idling (Hours)	Efficiency per Worker-Type (%)
Supervision(f)	117.52	0.00	100.00
l	206.70	197.18	51.18
ca	11.82	4.48	72.49
p	10.08	4.23	70.43
w	1.53	0.00	100.00
Total Effective Work with Supervision (Hours)		347.65	
Total Effective Work without Supervision (Hours)		233.65	
Total Idling Time (Hours)		203.98	

Figure 83 provides the total idling durations throughout each calendar day of work during phase 1. The various shadings provide junctures of when demolition began, the first period of construction and the second period of construction began and ended.

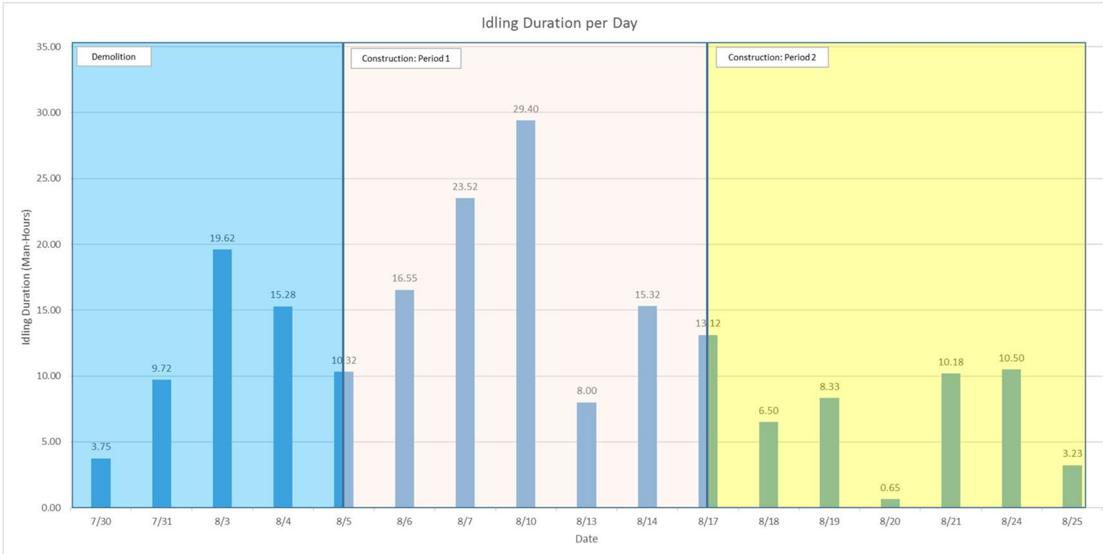

Figure 83: Duration of Idling per Day During Demolition and Period 1 and 2 of Construction

By implementing the wages, provided in Table 78, to the values provided in Table 80, the total amount of wages, per worker type, and the efficiency of the wages paid can be determined on a daily basis as provided in Table 82 and 83.

Table 82: Wage Costs Incurred Through Idling and Effective Work and Efficiency Determined through Monetary Values, Daily

Date	Effective Wages per Worker Type ($)						Wages Incurred by Effective Work ($)	Wages Incurred by Idling ($)	Monetary Efficiency (%)
	Supervision(f)	f	l	ca	p	w			
7/30	302.05	0.00	311.94	0.00	0.00	0.00	613.99	150.20	80.35
7/31	302.05	70.48	455.54	0.00	147.99	0.00	905.58	320.75	73.84
8/3	302.05	0.00	507.80	0.00	0.00	0.00	809.85	647.55	55.57
8/4	302.05	28.77	419.78	0.00	0.00	0.00	721.83	504.50	58.86

8/5	302.05	20.86	1045.87	0.00	0.00	0.00	1347.92	340.55	79.83
8/6	302.05	23.01	322.40	0.00	55.57	0.00	680.01	546.32	55.45
8/7	302.05	8.63	344.95	0.00	34.11	0.00	681.11	776.29	46.73
8/10	302.05	0.00	409.32	0.00	6.60	0.00	717.98	970.49	42.52
8/13	537.94	0.00	429.13	0.00	0.00	66.16	1033.23	264.08	79.64
8/14	302.05	0.00	472.59	231.57	0.00	0.00	1006.21	522.17	65.84
8/17	302.05	0.00	320.20	199.21	0.00	0.00	821.46	475.85	63.32
8/18	302.05	0.00	148.55	0.00	16.51	0.00	467.10	214.60	68.52
8/19	194.18	0.00	298.19	0.00	13.75	0.00	506.12	282.24	64.20
8/20	226.54	0.00	498.45	0.00	0.00	0.00	724.99	21.46	97.13
8/21	302.05	0.00	125.44	0.00	47.31	0.00	474.80	347.16	57.76
8/24	388.35	0.00	652.50	0.00	11.00	0.00	1051.85	346.61	75.22
8/25	99.25	0.00	60.52	79.11	0.00	0.00	238.87	111.46	68.18

As can be seen in Table 83, of the total wages to be paid by the owner of, $19,645.16, 34.82% or $6,842.28, went towards idling. Figure 15 provides the total costs, including the idling and effective costs on a daily basis throughout the phase.

Table 83: Total Wage Costs Incurred per Worker-Type, Idling and the Efficiency of Worker-Types Based on Monetary Values

Worker-Type	Wages Towards Effective Work ($)	Wage Towards Idling ($)	Efficiency per Worker-Type (%)
f	5070.84	0.00	100 %
l	6823.17	6509.05	51.18 %
ca	509.89	193.46	72.49 %
p	332.85	139.74	70.43 %
w	66.16	0.00	100 %
Total Costs in Wages		$19,645.17	
Wages Incurred by Effective Work ($)		$12,802.91	
Wages Incurred by Idling ($)		$6,842.25	

D.2 Fuel Consumption Rates

The following durations idling, non-idling, fuel-consumption rates, and total fuel consumption have been determined on a daily basis and presented below per generator or power tool-type.

Table 84: Electric Generator's Effective, and Idling Operating Times and Fuel Consumption, Daily

Date	Daily Operating Time (Hr)	Effective Operating Time (Hr)	Idling Operating Time (Hr)	Effective Fuel Consumed (Gal)	Idling Fuel Consumed (Gal)
7/30	0.00	0.00	0.00	0.00	0.00
7/31	0.00	0.00	0.00	0.00	0.00
8/3	0.00	0.00	0.00	0.00	0.00
8/4	0.00	0.00	0.00	0.00	0.00
8/5	3.07	2.17	0.90	1.67	0.50
8/6	6.50	2.92	3.58	2.25	1.97
8/7	7.00	6.05	0.95	4.66	0.52
8/10	6.50	4.57	1.93	3.52	1.06
8/13	0.75	0.50	0.25	0.39	0.14
8/14	7.02	3.35	3.67	2.58	2.02
8/17	6.00	2.32	3.68	1.78	2.03
8/18	2.00	1.50	0.50	1.16	0.28
8/19	3.42	1.37	2.05	1.05	1.13
8/20	7.00	5.03	1.97	3.88	1.08
8/21	2.57	1.92	0.65	1.48	0.36
8/24	2.33	2.25	0.08	1.73	0.05
8/25	0.00	0.00	0.00	0.00	0.00

Table 85: Allocated Tasks Dependent on Air Compressor Fuel Consumption During Effective Work and Idling, Daily

Date	Daily Operating Time (Hr)	Effective Operating Time (Hr)	Idling Operating Time (Hr)	Effective Duration (Hr)						Fuel Consumption of Effective Work (Gal)	Fuel Consumption of Idling (Gal)
				1 Breaker	2 Breakers	3 Breakers	Airblasting	Sand Blasting	Applying Silicone		
7/30	5.50	2.42	3.08	2.42	0.00	0.00	0.00	0.00	0.00	2.96	2.47
7/31	5.25	4.97	0.28	0.13	2.00	2.55	0.28	0.00	0.00	9.10	0.23
8/3	7.00	6.03	0.97	0.40	3.92	1.28	0.43	0.00	0.00	10.30	0.77
8/4	6.00	4.55	1.45	0.00	2.32	2.07	0.17	0.00	0.00	8.22	1.16
8/5	3.50	1.72	1.78	0.08	1.13	0.00	0.50	0.00	0.00	3.03	1.43
8/6	2.57	0.18	2.38	0.00	0.00	0.00	0.18	0.00	0.00	0.41	1.91
8/7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/14	2.28	0.52	1.77	0.00	0.00	0.00	0.05	0.47	0.00	1.19	1.41
8/17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/19	1.50	1.00	0.50	0.00	0.00	0.00	0.50	0.50	0.00	2.27	0.40
8/20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/21	2.00	1.08	0.92	0.00	0.00	0.00	1.08	0.00	0.00	2.42	0.73
8/24	2.25	1.03	1.22	0.00	0.00	0.00	0.13	0.75	0.15	2.16	0.97
8/25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 86: Idling and Effective (per Allocation) Durations and Effective and Idling Fuel Consumption for Skidder, Daily

Date	Daily Operating Time (Hr)	Effective Operating Time (Hr)	Idling Operating Time (Hr)	Effective Duration (Hr)			Fuel Consumption of Effective Work (Gal)	Fuel Consumption of Idling (Gal)
				Breaking (Hr)	Cleaning (Hr)	Construction (Hr)		
7/30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7/31	4.75	4.48	0.27	4.48	0.00	0.00	10.76	0.11
8/3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/6	2.45	1.68	0.77	0.00	1.12	0.57	2.81	0.31
8/7	1.15	1.03	0.12	0.00	1.03	0.00	1.55	0.05
8/10	0.20	0.20	0.00	0.00	0.20	0.00	0.30	0.00
8/13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/18	0.50	0.50	0.00	0.00	0.50	0.00	0.75	0.00
8/19	0.42	0.42	0.00	0.00	0.42	0.00	0.63	0.00
8/20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8/21	2.77	1.43	1.33	0.00	1.43	0.00	2.15	0.53
8/24	2.08	0.33	1.75	0.00	0.33	0.00	0.50	0.70
8/25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

D.3 Material Consumption Rates and Costs

Materials used in the field have been generalized and provided in Table 87.

Table 87: Material-Types (in General Order of Application) During Construction Stage

Stage	Materials
Const.	Portable Toilet
Const.	Traffic Control
Demo.	Torching/Heat Cutting
Const.	Armoring System
Const.	Strip Seal Extrusion
Const.	Wood, Cork and Sheet Metal for Formwork
Const.	Rebars, Dowels and Stirrups for Concrete Reinforcement
Const.	Concrete (Class A.)
Const.	Adhesive and Curing Compounds
Const.	Water Source for New Concrete
Const.	Liquid Sealants
Cg.	Sandblasting Abrasive

Costs were determined from the "Superintendent Book" that contained costing agreements, and manufacturers and distributors of the majority of materials used in the field. For all values that were ambiguous or not detailed enough, the manufacturers were contacted and a sales or technical representative was consulted with. For costing data that was non-existent, manufacturers of similar products listed in the "Superintendent Book" were consulted with. Water was utilized in the concrete curing process of the newly formed headers and Wing Wall/Parapets. With the amount of water usage logged, the Wilmington County utility billing department was contacted. Information regarding the contractor's commercial property and water usage amounts, and costing rates were provided.

The tables below provide the product name, manufacturer, delivery amount, cost per quantity of material purchased, the rate of usage, the total usage, and the total cost of each material.

Before demolition could begin, traffic control and a portable toilet were implemented to the site with associated costs shown in Table 88.

Table 88: Material Costs Implemented Before and Throughout Demolition

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Traffic Control	Arrowpanels, Type C	-	$17.00	$/EADY	3.00	ArwPnl/Phase	-	-	**81.00**	**ArwPnl-Phase**	$1,377.00
Traffic Control	Furn & Maint Port Changeable Message Sig	-	$75.00	$/EADY	2.00	MB/Phase	-	-	**54.00**	**MB-Phase**	$4,050.00
Traffic Control	Plastic Drums	-	$0.30	$/EADY	78.00	PD/Phase	-	-	**2106.00**	**LF(PD)-Phase**	$631.80
Traffic Control	Temporary Barricades, Type III	-	$0.25	$/LFDY	78.00	LF(Brcd)/Phase	-	-	**2106.00**	**LF(Brcd)-Phase**	$526.50
Traffic Control	Temporary Warning Signs and Plaques	-	$1.75	$/EADY	21.00	WS/Phase	**-**	**-**	**567.00**	**WS-Phase**	$992.25
Worker Facilities	Portable Toilet Rental	-	$0.50	$/Day	1.00	PT/Month (Phase)	-	-	27.00	Day	$13.50
Worker Facilities	Portable Toilet Services	-	$2.56	$/Day	1.00	PT/Month (Phase)	-	-	27.00	Day	$69.08

During the construction stage, reabars, stirrups and dowels were epoxied and tied into the demolished reservoirs. The costs associated with all steel reinforcement are shown in Table 89.

Table 89: Steel Reinforcement Costs for all Components Demolished and Reconstructed

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Steel Renforcement (Deck)	Bar Reinforcement	RESTEEL	$0.94	$/Lb	922.81	Lb/Deck	-	-	922.81	Lb	$871.11
Steel Renforcement (Backwall)	Bar Reinforcement	RESTEEL	$0.94	$/Lb	105.31	Lb/Backwall	-	-	105.31	Lb	$99.41
Steel Reinforcement (in Wing Wall)	Bar Reinforcement	RESTEEL	$0.94	$/Lb	45.37	Lb/Wing Wall	-	-	45.37	Lb	$42.83
Steel Reinforcement (in Parapet)	Bar Reinforcement	RESTEEL	$0.94	$/Lb	81.53	Lb/Parapet	-	-	81.53	Lb	$76.96

All adhesives costs for steel reinforcement are shown and costed in Table 90. The epoxies and adhesives associated with the anchorage of the armoring system (of the backwall) and of the dowels into the deck are shown in Table 90.

Table 90: Adhesive Costs for Steel Reinforcement and Anchorage of Armoring System

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Adhesive (Grout)	HD-25	Dayton Superior	$0.38	$/Lb	0.01	Bag/Hole	0.36	Lb/Hole (Anchorage)	7.14	Lb	$2.73
Adhesive (Epoxy for Deck)	A7-28 Acrylic Adhesive	ITW Redhead	$125.71	$/Gal	0.06	Btl/Hole	0.01	Gal/Hole	0.96	Gal	$120.45
Adhesive (Epoxy for Wing Wall)	A7-28 Acrylic Adhesive	ITW Redhead	$125.71	$/Gal	0.08	Btl/Hole	0.02	Gal/Hole	0.15	Gal	$18.33

The materials that were used when constructing the formwork included cork, wood, sheet metal and all associated adhesives. The costs of associated formwork material are shown in Table 91.

Table 91: Formwork Material Costs

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Formwork (Cork)	Preformed Expansion Jt material-cork	Home Depot	$0.59	$/ft^2	1.35	ft^2/ft	-	-	51.74	ft^2	$30.52
Formwork (Wood)	Wood	Home Depot	$1.00	$/ft^2	3.51	ft^2/ft	-	-	134.67	ft^2	$134.46
Formwork (Sheet Metal)	Plain Aluminum Sheet in Silver (36"x36")	MD Building Products	$2.44	$/ft^2	2.43	ft^2(Steel)/ft	-	-	95.58	ft^2	$233.43
Adhesive (Construction)	SikaBond Construction Adhesive	Sika Group	$76.04	$/Gal	3.00	Cntnr/Pp	0.24	Gal/Pp (Cnsmbl)	0.24	Gal	$18.00
Adhesive/Filler	Insulating Foam Sealant, Big Gap Filler	Great Stuff (Dow)	$6.61	$/Lb	2.00	Container/Phase (Cnsmbl)	1.50	Lb/Phase (Cnsmbl)	1.50	Lb	$9.92

All materials associated with concrete pouring are costed and shown in Table 92. Such costs include the adhesives, sprayed before each pour, the concrete itself, and all of the material implemented for curing purposes.

Table 92: Costs of Concrete and all Materials Applied for Concrete

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Adhesive (Spray for Concrete)	Everbond	L&M Construction Chemicals	$32.00	$/Gal	0.00	Gal/ft^2	-	-	0.75	Gal	$24.00
Concrete	Class A Concrete	Heritage Concrete	$3.46	$/ft^3	140.08	ft^3/WHr	-	-	158.75	ft^3	$549.76
Curing Compound (Spray for Concrete)	Specfilm-E-Con	SpecChem	$18.40	$/Gal	0.00	Gal/ft^2	-	-	0.88	Gal	$16.10
Water	Water Tank	City of Wilmington	$0.01	$/Gal	7.08	Gal/Ft^3	67.65	Hr/Dam Curing	1123.28	Gal	$10.72

Costs associated with the armoring and seal are provided in Table 93. This includes the armoring system, the strip seal extrusion and the adhesive necessary at the strip seal-armoring interface.

Table 93: Armoring System, Strip Seal Extrusion and Extrusion Adhesive Costs

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Strip Seal Extrusion	Neoprene Strip Seal Dam, 3" Movement	RPS Machinery-DS Brown	$15.00	$/LF	2.00	LF/WHr	-	-	36.41	ft	$546.17

Strip Seal Armoring	Strip Seal Armoring, 3" Movement (Both Sides)	RPS Machinery- DS Brown- Ackerman and Baynes	$182.00	$/LF	7.12	LF/WHr	-	-	39.41	ft	$7,172.91
Adhesive (for Strip Seal Extrusion)	DSB 1516	DS Brown	$32.00	$/Gal	0.01	Gal/Ft	-	-	0.35	Gal	$11.20

Before providing the sealant between the backwall and approach, a primer had to be applied to the void where the cork was grinded down. After the silicone sealant was poured (with the AT1200S, connected to the air compressor) and dried, methacrylate was applied on top of the newly poured silicone. All such costs are expressed in Table 94.

Table 94: Silicone and Methacrylate Sealant Costs

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Adhesive (Primer)	Corning P5200 Adhesion Promotoer Primer Red	Dow Corning	$52.79	$/Lb	0.00	Bottle/Ft	0.00	Lb/ft	0.06	Lb	$3.29
Sealant (Silicone)	Sikasil-728RCS A	Sika Group	$160.00	$/Gal	5.00	Tubes/Backwall	0.02	Gla/Ft	0.78	Gal	$125.00
Sealant (Silicone)	Sikasil-728RCS B	Sika Group	$160.00	$/Gal	5.00	Tubes/Backwall	0.02	Gal/Ft	0.78	Gal	$125.00
Sealant (Methacrylate)	NEW Sikadur 55 SLV Header/Sealer	Sika Group	$116.67	$/Gal	450.05	Ft/Hr	0.97	Gal/Hr	0.08	Gal	$9.12

For those tasks not included in construction stage, they have been included in Table 95 providing costing values for torching/heat cutting and for the abrasive usages of the sandblasting approach.

Table 95: Costs Associated with Demolition and Cleaning

Item	Product Title	Product Distributor or Developer	Cost per Quantity ($)	Unit	Initial Usage Rate	Unit	Usg Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Sandblasting	Ebonygrit Copper Slag	Opta Minerals Inc	$0.15	$/Lb	3.75	Bg/Hr	206.25	Lb/Hr	354.06	Lb	$51.50
Gasses for Torching	UN1001 Acetylene Dissolved	Praxair	$0.57	$/ft^3	56.55	Trchng Ft/Dam	2.56	ft^3/ft demo	145.00	ft^3	$82.30
Gasses for Torching	UN1072 Oxygen Compressed	Praxair	$0.20	$/ft^3	56.55	Trchng Ft/Dam	4.03	ft^3/ft demo	228.00	ft^3	$45.06

Appendix E

SOCIETAL COSTING FACTORS AND RESULTS OF CASE-STUDY

E.1 Driver Delay Costing Equations

The following equations for the driver delay, vehicle operating and accident costs, determined by the BridgeLCC software (Ehlen & Rushing, 2003) can be formulated as follows,

$DDC = Driver\ Delay\ Costs$

$L = Length\ of\ roadway$

$Sa = Traffic\ speed\ during\ bridge\ workL = Length\ of\ roadway$

$Sn = Traffic\ speed\ during\ normal\ trafficL = Length\ of\ roadway$

$w = Cost\ incurred\ to\ drivers\ per\ hour\ during\ driving$

$N = Number\ of\ days\ of\ roadwork$

$ADT = Average\ daily\ traffic\ (number\ of\ cars\ per\ day)$

The determined cost incurred to drivers per hour of driving provides the total cost incurred to drivers due to delays in traffic.

Equation 1

$$DDC = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) * ADT * N * w$$

The driver delay costs are determined by considering the time lost to drivers on the structure upon which the work-zone is present. By dividing the length of the structure by the traffic speed in the presence of a work-zone, and by the traffic speed where no work-zone were present, the difference of the time incurred to drivers during the work-zone, and without the work-zone, provides a snapshot of the time lost to a vehicle due to roadwork. By multiplying the time lost by the ADT and to number of days of roadwork, the total amount of time lost due to the entire duration of the project by all vehicles traversing the structure is considered. By multiplying the total time lost by the weighted average vehicle cost of time, the total costs to the road users due to delays can be determined.

In the ETSI Stage 1 study, driver delay costs, analogous to passenger delay costs, are defined as the time lost to drivers due to road work and expressed mathematically.

Where,

$L = Length\ of\ roadway\ of\ affected\ roadway(s)$

$v_r = Traffic\ speed\ during\ roadwork$

$v_n = Traffic\ speed\ during\ normal\ conditions$

$ADT_t = Average\ daily\ traffic\ at\ time\ t$

$N_t = Number\ of\ days\ of\ roadwork\ at\ time\ t$

$r_L = The\ proportion\ of\ commercial\ traffic\ to\ Total\ Traffic$

$w_L = Value\ of\ time\ per\ hour\ for\ commercial\ traffic$

$w_D = Value\ of\ time\ per\ hour\ for\ drivers$

$T = The\ amount\ of\ time\ considered\ in\ the\ study\ for\ maintenance\ and\ repair\ work$

Equation 1-6-1

$$LCC_{user,delay} = \sum_{t=0}^{T} \left(\frac{L}{v_r} - \frac{L}{v_n}\right) AD\ \ _{t} * \frac{N_t(r_L w_L + (1 - r_L) w_D)}{(1 + r)^t}$$

Similar to the BridgeLCC software base equation above, the user delay costs, analogous to the passenger delay costs, are also determined by considering the time lost to vehicles on the structure during roadwork and by multiplying that value by the average daily traffic, amount of days of roadwork, and by the value of time. Unlike the BridgeLCC driver delay costing equation, the equations provided by the ETSI Project considers commercial and common drivers as two separate entities with differing costing factors. Also, unlike the BridgeLCC driver delay costing equation, ETSI considers the speed during roadwork not only on the structure roadway, but also under the roadway.

To calculate the traffic delay time due to a work-zone, the mobility impact analysis method is suggested, as a means to estimate the capacity and demand relationship assisting in simulation purposes, the floating car technique (Mallela & Sadavisam, 2011).

E.2 Vehicle Operating Costing Equations

The BridgeLCC software provides the vehicle operating costs as an equation dependent on the time lost to drivers on the structure upon which the work-zone is present. The total amount of time lost due to the entire duration of the project by all vehicles are needed and determined in the same manner as the DDC. Thus, by multiplying the total amount of time lost due to the entire duration of the project by all vehicles traversing the structure by the weighted average of vehicle costs, the estimated vehicle operating costs can be determined (Ehlen & Rushing, 2003).

Where,

r=Weighted average of vehicle costs

Equation 6-2

$$Vehicle\ Operating\ Costs = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) * ADT * N * r$$

The vehicle operating cost provided by the ETSI Project (Stage 1) is similar to the passenger delay costs it provided except for the value of time factors "w" are exchanged with operating cost factors, "o". Unlike ETSI's road user delay costing equation, an extra variable is introduced that taken into account costs incurred to cars specifically (Jutila et al., 2007), as shown below

Where,

$o_L = Operating\ costs\ for\ commercial\ traffic\ ve$hicles

o_G = Operating costs for transported goods

o_D = Operating costs for cars

Equation 6-3

$$LCC_{user,operating} = \sum_{t=0}^{T} \left(\frac{L}{v_r} - \frac{L}{v_n}\right) AD_{\ t} * \frac{N_t(r_L(o_L + o_G) + (1 - r_L)o_D)}{(1 + r)^t}$$

E.3 Vehicular Volumes of Case-Study

Since the average daily traffic determined for a roadway represents the volume of traffic traveling in all directions of that roadway for any hour of that day. It is the intent of this research to determine the hourly volume of vehicles on weekdays and weekends of a particular month in each direction of the roadway before delay and operating costs are determined. The design hourly volume (DHV) is the volume of trucks and automobiles traversing the structure at certain hours during weekdays and weekend. The volume, however, must be appropriately divided between the opposing directions. The directional split, or "D", is the percentage of traffic volume traveling in the most populated, primary, direction of the structure. By determining the hourly volume per each direction of the roadway, the directional design hourly volume (DDHV) is attained. As can be seen in Figure 22, the annual average daily traffic, directional split, amongst many other factors are included for this roadway. The values presented in the image above, were used for all following calculations dependent on such values.

With varying amounts, all TPG's, except for urban local streets (TPG 4), consist of automatic traffic recorder (ATR) stations that are permanently installed in specific locations. ATR stations are fitted with loop detectors that counts each vehicle that passes through it for every day throughout the year where the collection of ATR stations make up the Road Inventory network. ATR stations transmit data to the Office of Information Technology (OIT) headquarters, where the data is then post-processed (*Delaware Vehicle Volume Summary 2014 (Traffic Summary)*, n.d.). The data from the ATR stations and Road Inventory network is pivotal in the collection of traffic data such as the ADT and average annual daily traffic (AADT).

Based on the average traffic counts of ATR stations that count continuously throughout the year, and those ATR stations that are subjected to the coverage count program, adjustment factors have been developed to further adjust AADT values. Adjustment factors have been developed and tabulated based on the aforementioned factors for determining the AADT distribution by hour on weekdays and weekends, known as the diurnal distribution of traffic, or the design hourly volume (DHV)over a 24-hour period. Such traffic values were found by averaging the traffic counting data from ATR stations within each TPG and can be seen in the Tables 96 and 97, representing the weekday and weekend DHVs, respectively (*Delaware Vehicle Volume Summary 2014 (Traffic Summary)*, n.d.).

Table 96: 2014 DHV on Weekdays

Diurnal (Hourly) Distribution of Traffic Table

2014 WEEKDAYS

HOUR	TPGROUP1	TPGROUP2	TPGROUP3	TPGROUP4	TPGROUP5	TPGROUP6	TPGROUP7	TPGROUP8
0	1.16	0.68	0.72	-	0.71	0.65	0.57	0.63
1	0.79	0.38	0.35	-	0.53	0.46	0.36	0.38
2	0.72	0.27	0.25	-	0.53	0.44	0.31	0.29
3	0.91	0.35	0.33	-	0.63	0.62	0.6	0.33
4	1.51	0.7	0.33	-	1.23	1.24	1.05	0.56
5	3.6	1.04	0.88	-	2.73	2.94	2.49	1.4
6	6.06	3.91	2.66	-	6.27	5.1	6.57	3.23
7	7.04	6.33	6.26	-	8.84	6.22	7.84	5.49
8	6.21	6.06	7.91	-	6.06	5.53	6.24	6.79
9	5.2	5.23	5.36	-	5.28	5.37	4.54	5.98
10	4.75	5.25	4.77	-	5.49	5.67	4.39	6.56
11	4.83	5.94	4.81	-	5.85	5.97	4.71	6.98
12	4.93	6.36	5.39	-	6.06	6.11	4.91	7.18
13	5.16	6.28	5.62	-	6.14	6.27	5.21	7.04
14	5.85	6.66	6.13	-	6.7	6.91	5.36	7.22
15	6.7	7.32	7.36	-	7.57	7.62	6.01	7.74
16	7.16	8.18	8.64	-	8.16	8.16	6.60	7.82
17	6.88	6.14	9.42	-	7.23	7.15	9.17	7.14
18	5.61	6.33	7.06	-	5.01	5.11	5.91	5.31
19	4.26	4.85	5.12	-	3.8	3.93	4.17	4.13
20	3.5	3.78	3.89	-	3.19	3.3	3.13	3.42
21	3.06	2.78	3	-	2.47	2.47	2.27	2.89
22	2.43	1.7	2.17	-	1.72	1.63	1.56	1.75
23	1.6	1.05	1.46	-	1.2	1.1	0.99	1.04

(Delaware Vehicle Volume Summary 2014 (Traffic Summary), n.d.)

Table 97: 2014 DHV on Weekends

Diurnal (Hourly) Distribution of Traffic Table

2014 WEEKENDS

HOUR	TPGROUP1	TPGROUP2	TPGROUP3	TPGROUP4	TPGROUP5	TPGROUP6	TPGROUP7	TPGROUP8
0	1.86	1.35	1.64	.	1.25	1.23	1.31	1.04
1	1.31	0.97	0.99	.	0.86	0.85	0.80	0.71
2	1.06	0.6	0.72	.	0.66	0.6	0.55	0.44
3	0.88	0.47	0.47	.	0.57	0.5	0.47	0.29
4	0.92	0.54	0.37	.	0.73	0.67	0.59	0.33
5	1.42	0.82	0.62	.	1.22	1.14	0.98	0.68
6	2.17	1.52	1.33	.	2.13	1.56	1.59	1.46
7	2.93	2.35	2.2	.	3.18	3.12	2.99	2.76
8	3.86	3.57	3.72	.	4.51	4.59	4.34	4.43
9	5.03	4.98	5.58	.	5.90	6.09	5.68	6.14
10	5.9	6.33	6.84	.	7.06	7.08	6.57	7.42
11	6.44	7.37	7.49	.	7.56	7.4	7.23	8.06
12	6.66	8.08	7.60	.	7.73	7.61	7.50	8.11
13	6.91	8.13	7.6	.	7.59	7.6	7.61	7.83
14	7	8.09	7.47	.	7.48	7.53	7.42	7.08
15	7.02	7.92	7.62	.	7.32	7.32	7.36	7.03
16	6.83	7.57	7.16	.	6.98	7.13	7.36	7.23
17	6.6	6.88	6.79	.	6.46	6.53	7.13	6.61
18	5.92	6.14	5.98	.	5.56	5.66	6.21	5.76
19	5.22	5.08	5.09	.	4.64	4.87	5.01	4.85
20	4.8	4.09	4.27	.	3.51	3.9	3.98	3.96
21	3.91	3.21	3.44	.	3.01	3	3.08	3.06
22	3.21	2.38	2.67	.	2.2	2.12	2.33	2.13
23	2.37	1.59	2.19	.	1.52	1.48	1.56	1.35

(Delaware Vehicle Volume Summary 2014 (Traffic Summary), n.d.)

Thus, knowing that Edgemoor Road falls under TPG 2, the following data can be determined, which, as will be explained, was implemented in the pursuit of determining the hourly volume and speed throughout the weekdays and weekends of a particular month. Note that such results are determined for the roadway during normal conditions, without the presence of a work-zone.

- AADT= 8,417 Vehicles per Day
- % Truck (T)= 9%
- Directional Split= 55% in the Primary (Westbound) Direction
- The following diurnal factors (DHV factors) to determine the volume distribution on weekdays and weekends,

Table 98: DHV Factors, Determining Volume Distribution on Weekdays and Weekends, Hourly

Hour	Weekday Factors	Weekend Factors
0	0.0058	0.0135
1	0.0036	0.0097
2	0.0027	0.006
3	0.0035	0.0047
4	0.007	0.0054
5	0.0164	0.0082
6	0.0391	0.0152
7	0.0633	0.0235
8	0.0605	0.0357
9	0.0523	0.0796
10	0.0525	0.0633
11	0.0594	0.0737
12	0.0636	0.0808
13	0.0628	0.0813
14	0.0665	0.0809

15	0.0732	0.0792
16	0.0818	0.0757
17	0.0814	0.0688
18	0.0633	0.0614
19	0.0485	0.0508
20	0.0379	0.0409
21	0.0276	0.0321
22	0.017	0.0236
23	0.0105	0.0159

By multiplying the AADT with the weekend and weekday diurnal factors, the distribution of volume throughout a weekday and weekend can be determined. However, the 2014 Vehicle Volume Summary Book provides a list of corresponding ATR stations for each TPG that includes the monthly ADT (MADT) from which the AADT can be determined. The MADT will adjust the AADT to reflect the DHV of that month. For TPG 2 ATR stations, the following MADT's and AADT's have been determined for each station.

Table 99: MADT Data from DelDOT, and Corresponding Percentage of AADT, During July and August

ATR Stations	8005	8011	8011	8011	8011	8011	8020	8020	8020	8026	8030	8031	8040	8049	8060	8061
Month	Monthly Average Daily Traffic (MADT)															
7	17799	N/A	16694	36523	27919	25050	25050	N/A	17432	29351	43832	26542	47020	15373	18719	23042
8	18082	8354	15829	36759	28837	25397	25397	8354	17324	29104	44284	26332	49112	15450	18877	24019
Month	% AADT															
7	111.7	N/A	109.1	101.6	97.5	99.5	99.5	N/A	109.7	104.9	101.7	100.2	97.6	119.4	105.0	99.7
8	113.5	103.7	103.5	102.3	100.7	100.8	100.8	103.7	109.0	104.0	102.8	99.5	101.9	120.0	105.9	104.0

By determining the percentage that each MADT represents from the total AADT value, and by determining the average of these percentage value, the MADT factors are determined for Edgemoor Road for the months of July and August. Thus, the factors used to multiply the AADT, to accurately reflect the monthly adjustment of when such reconstruction processes are occurring are as follow,

Table 100: Factors Applied to AADT Value to Get MADT

Month	MADT Factor
July	1.0408
August	1.0476

To determine the number of vehicles traversing the structure in the eastbound and westbound direction, the primary direction, upon which the direction split refers to, must be determined. After consulting with Scott Neidert, of the Delaware Department of Transportation, a Project Manager of the Traffic Section, it was determined that the westbound direction of the bridge was considered primary. With the DHV determined from the MADT averages, the volume of vehicles traversing the westbound (primary) direction was found by multiplying the DHV's by the directional split of .55, while the volume of vehicles eastbound (secondary) direction was determined by performing the dot product of the DHV by .45, thus determining the $DDHV_P$ and $DDHV_S$. For the purpose of this study, the directional design hourly volume (DDHV) will be referred to as the average hourly traffic (AHT). Thus,

Where,

Equation 6-4

$$AHT_P = DDHV_P = DHV\ in\ Primary\ Direction\ (Vehicles)$$

Equation 6-5

$$AHT_S = DDHV_S = DHV\ in\ Secondary\ Direction\ (Vehicles)$$

Equation 6-6

$$AH\ \ _P = (\mathbf{D_P})(\mathbf{DHV})$$

And,

Equation 6-7

$$AHT_S = \mathbf{DHV} - \mathbf{DDHV_P}$$

After the volume of vehicles traveling in the primary and secondary direction, it was then necessary to determine the number of automobiles and freight trucks comprising the volume in both directions. The percentage of trucks, or the T factor, from the DelDOT KMZ file, will be factored into the AHT's as in-state planning and design are referred to for such endeavors by DelDOT engineers. Thus, the AHT's for automobiles and trucks were then determined during the particular months and days during the reconstruction phases that were observed between the dates of 7/30/2015 and 8/25/2015 for phase 1 of the project.

Table 101, below, provides the AHT's for weekdays and weekends during the month of August. The following values were determined through the manner of calculating the automobile and freight AHT through the usage of the consideration of the TPG which in turn lead to the usage of the calculated AADT, MADT, DHV, and T factors during phase 1 of the joint replacement operation. The total amount of vehicles traversing the structure with the presence of the work-zone and those detouring it due to the closure of the eastbound and westbound direction are equal to the number of vehicles traversing the structure when a work zone is not present, or normal conditions. Thus, the number of vehicles traversing the structure when the work zone is present, despite partial lane closure, is assumed to be unchanging than when the work zone was not present at all.

Table 101: Hourly Volume of Automobile and Trucks in the Eastbound and Westbound Direction on Weekdays and Weekends in the Month of August

Hour	Weekday Hourly Volume				Weekends Hourly Volume			
	Automobiles (WB)	Trucks (WB)	Automobiles (EB)	Trucks (EB)	Automobiles (WB)	Trucks (WB)	Automobiles (EB)	Trucks (EB)
0	25.60	2.53	20.94	2.07	59.58	5.89	48.74	4.82
1	15.89	1.57	13.00	1.29	42.81	4.23	35.02	3.46
2	11.92	1.18	9.75	0.96	26.48	2.62	21.66	2.14
3	15.45	1.53	12.64	1.25	20.74	2.05	16.97	1.68
4	30.89	3.06	25.27	2.50	23.83	2.36	19.50	1.93
5	72.37	7.16	59.22	5.86	36.19	3.58	29.61	2.93
6	172.55	17.07	141.18	13.96	67.08	6.63	54.88	5.43

7	279.35	27.63	228.56	22.60	103.71	10.26	84.85	8.39
8	266.99	26.41	218.45	21.60	157.55	15.58	128.90	12.75
9	230.80	22.83	188.84	18.68	218.89	21.65	179.09	17.71
10	231.69	22.91	189.56	18.75	279.35	27.63	228.56	22.60
11	262.14	25.93	214.48	21.21	325.24	32.17	266.11	26.32
12	280.67	27.76	229.64	22.71	356.58	35.27	291.74	28.85
13	277.14	27.41	226.75	22.43	358.78	35.48	293.55	29.03
14	293.47	29.02	240.11	23.75	357.02	35.31	292.11	28.89
15	323.04	31.95	264.30	26.14	349.52	34.57	285.97	28.28
16	360.99	35.70	295.36	29.21	334.07	33.04	273.33	27.03
17	359.22	35.53	293.91	29.07	303.62	30.03	248.42	24.57
18	279.35	27.63	228.56	22.60	270.96	26.80	221.70	21.93
19	214.03	21.17	175.12	17.32	224.18	22.17	183.42	18.14
20	167.26	16.54	136.85	13.53	180.49	17.85	147.68	14.61
21	121.80	12.05	99.66	9.86	141.66	14.01	115.90	11.46
22	75.02	7.42	61.38	6.07	104.15	10.30	85.21	8.43
23	46.34	4.58	37.91	3.75	70.17	6.94	57.41	5.68

After determining the AHT of automobile and freight vehicles for each month, the number of weekdays, weekends to scale the AHT values were determined to acquire the total number of vehicles affected by the work-zone for each phase of demolition and construction.

E.4 Speed Characteristics of Case-Study

An associated average speed was correlated to each hour of the day through the use of Google Map's "Typical Traffic" function. Google's Typical Traffic function allows the user to determine, based on past averages, the magnitude of traffic delays between 6:00 AM and 10:00 PM during any day of the week (https://support.google.com/maps/answer/3092439?hl=en). Upon choosing each hour for each day of the week, the colors transposed on the satellite image highlighting the route, in both directions, of the bridge structure was recorded as can be seen in Figure 84. The color spectrum provided indicates the magnitude of traffic delays with the following colors designated to traffic delays from lowest (no traffic delays) to highest

- Green
- Orange
- Red

- Maroon

In Figure 84, the traffic conditions on Edgemoor Road on a typical Monday at 8:00 AM depicts the eastbound direction to have an associated traffic delay color of orange, and an associated traffic delay color of green in the westbound direction.

Figure 84: Google Map Image and Average Congestion Feature Example
(https://www.google.com/maps/@39.752409,-75.5038284,213m/data=!3m1!1e3!5m1!1e1)

To determine a relationship between the Google's Traffic Delay function and speed, assumptions were made regarding the color association to speed during normal traffic conditions (before the presence of the work-zone). A similar approach, utilizing Google's Traffic Delay graphical function to speed, was done so in the "Travel Time Estimation Using Bluetooth" report by members of the Louisiana State University, which was funded by the National Center for Intermodal Transportation for Economic Competitiveness, 2016. Traffic speeds were collected through a variety of avenues including the Google's Traffic Delay graphical function (Gudishala, Wilmot, & Mokkapati, 2016). Using Google's Traffic Delay function, the research effort assigned colors to speed ranges for freeways for each hour of each day of the week of the analysis period and logged them (Gudishala, Wilmot, & Mokkapati, 2016).

Assuming a speed associated with even the maroon color, the speed limit was divided by the number of colors in the spectrum plus one to provide a speed for each color. Thus, the speeds assumed for each traffic delay condition is as so.

Table 102: Color Designation to Speed per Google Maps Traffic Delays

Traveling Speed Assumptions	
Google Maps Traffic Delay Colors	Assumed Traveling Speed (mph)
Green	35
Orange	26.25
Red	17.5
Maroon	8.75

After the colors were tabulated, the numerical values from Table 102 were assigned to them, and the speeds were subsequently averaged for weekdays and weekends. The average speeds during weekdays and weekends (with all hours not included in the Google interface considered to have free flow) are provided in Table 103.

Table 103: Designated Speeds, without Work-Zone, on Edgemoor Road Eastbound and Westbound Direction During Weekdays and Weekends

Hour	Weekdays		Weekends	
	Eastbound	Westbound	Eastbound	Westbound
0	35	35	35	35
1	35	35	35	35
2	35	35	35	35
3	35	35	35	35
4	35	35	35	35
5	35	35	35	35
6	29.75	35	30.625	35
7	26.25	33.25	35	35
8	26.25	33.25	35	35
9	26.25	35	35	35
10	28	35	30.625	35
11	28	33.25	30.625	35
12	29.75	35	30.625	35
13	29.75	33.25	26.25	35
14	28	35	35	35
15	29.75	29.75	26.25	35
16	26.25	31.5	35	35
17	26.25	31.5	26.25	35
18	26.25	33.25	30.625	35
19	28	35	35	35
20	33.25	35	26.25	35
21	29.75	35	30.625	35

22	35	35	35	35
23	35	35	35	35

(https://www.google.com/maps/@39.752409,-75.5038284,213m/data=!3m1!1e3!5m1!1e1)

When a work zone was present, it was assumed that the traffic delay for vehicles traversing the structure would increase by a magnitude of one color per traffic lane closure; for example, if the direction were depicted with green during normal traffic conditions, it would be assumed to be red when the work zone was present.

E.5 Vehicle Speeds to Costs Correlation

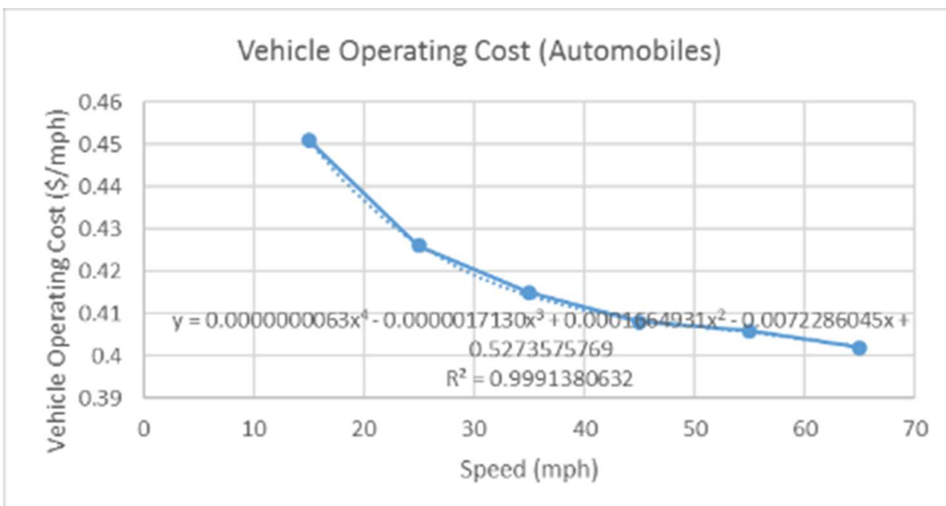

Figure 85: Correlated Vehicle Operating Cost to Speed for Automobiles

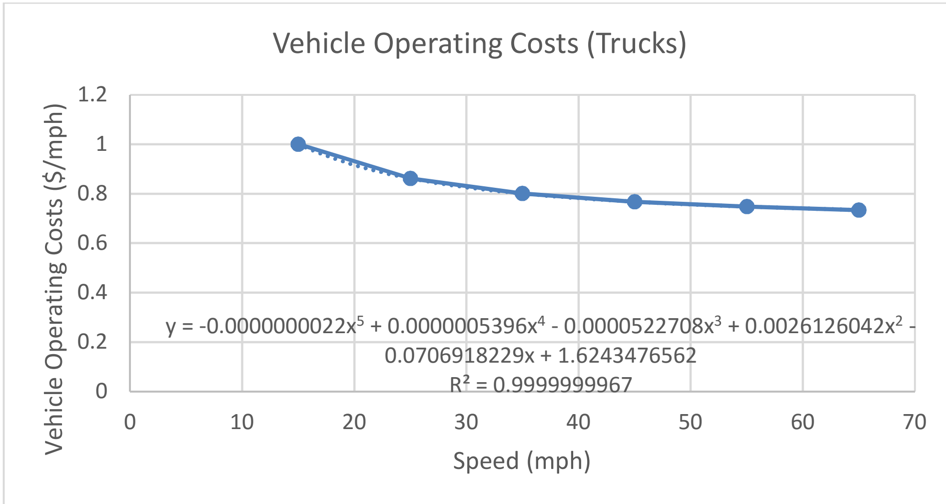

Figure 86: Correlated Vehicle Operating Cost to Speed for Trucks

Appendix F

ENVIRONMENTAL COSTING FACTORS AND RESULTS OF CASE STUDY

The outputs for the emission factors provided by MOVES were provided in grams per hour. The following emission factors were determined for the power sources provided in Table 104.

Table 104: Emission Rates for Each Power Source

Emitted Pollutants	Emission Factors of Power Sources (grams/hour)			
	Electric Generator	Air Compressor	Skidder	Power Driven Welder
Atmospheric CO2	9223.44	26097.67	39924.47	14724.02
Carbon Monoxide (CO)	2427.77	48.24	342.49	129.39
Fine Particulate Matter (PM 2.5)	0.91	7.79	50.17	17.40
Oxides of Nitrogen (NOx)	19.71	179.59	318.02	120.90
Road Dust (PM 10)	0.99	8.03	51.72	17.94
Sulfur Dioxide(SO2)	0.17	0.16	0.26	0.10
Volatile Organic Compounds (VOC)	39.24	11.16	71.86	31.60

As provided in Tables 105, the total amount of grams of each specific pollutant during normal operations on the structure have been determined. Table 106 provides the costing of the emitted pollutant during normal operations of the bridge for the duration of the case-study. The same costing factors utilized in Table 41 were used.

Table 105: Emitted Pollutants for Normal Operations on Structure During the Duration of the Case-Study

Emitted Pollutants	Pollutants Emitted from Vehicles per Direction(grams)		Total Emitted Pollutants (grams)
	Eastbound	Westbound	
Carbon Monoxide (CO)	50927.84	57760.53	108688.37
Oxides of Nitrogen (NOx)	9259.57	10929.47	20189.03
Road Dust (PM 10)	350.26	406.08	756.34
Oxides of Sodium (Sox)	70.71	64.79	135.50
Volatile Organic Compounds (VOC)	4853.36	5482.05	10335.41

Table 106: Costs of Emitted Pollutants During Normal Operations on Structure for the Duration of the Case-Study

Emitted Pollutants	Pollutant Costs Emitted from Vehicles per Direction ($)		Total Emitted Pollutant Costs ($)
	Eastbound	Westbound	
Carbon Monoxide (CO)	$4.21	$4.78	$8.99

Oxides of Nitrogen (NOx)	$176.58	$208.42	$385.00
Road Dust (PM 10)	$54.02	$62.62	$116.64
Oxides of Sodium (Sox)	$5.44	$4.99	$10.43
Volatile Organic Compounds (VOC)	$6.47	$7.31	$13.79
Total Costs	$246.72	$288.12	$534.84

As previously mentioned, the case-study consisted of a work-zone that mandated that the eastbound direction be detoured while 2 of the 3 lanes of the westbound direction be closed. Again, the increase in traveling time for the westbound direction was considered not to have been enough to cause motorists to take the detour. The only direction detouring was the eastbound direction and the westbound direction was considered to experience the same volume per normal operation. The detour lengths, and the speeds of all of the components of the detour were considered when recalculating the emitted pollutants for the eastbound direction, when detoured, and the westbound direction, which consisted of the same volume of vehicles but a drop in sped due to the increase in congestion, in the same manner that the vehicle operating and road user delay costs were calculated. Tables 107 provides the total amount of pollutants emitted, per direction during construction; thus, the eastbound direction provides the emitted pollutants due to the 3-mile detour (of varying speeds) and the congested westbound direction. Table 108 provides the corresponding costs of Table 107.

Table 107: Emitted Pollutants During Construction

Emitted Pollutants	Pollutants Emitted from Vehicles per Direction(grams)		Total Emitted Pollutants (grams)
	Eastbound (Detoured)	Westbound	
Carbon Monoxide (CO)	3065833.56	60007.78	3125841.35
Oxides of Nitrogen (NOx)	567058.3999	13321.57614	580379.976
Road Dust (PM 10)	21298.28985	595.072509	21893.36236
Oxides of Sodium (Sox)	4358.610201	124.6480417	4483.258243
Volatile Organic Compounds (VOC)	292203.5839	7818.588732	300022.1726

Table 108: Costs of Emitted Pollutants During Construction

Emitted Pollutants	Pollutant Costs Emitted from Vehicles per Direction($)		Total Emitted Pollutant Costs ($)
	Eastbound (Detoured)	Westbound	
Carbon Monoxide (CO)	$253.46	$4.96	$258.42
Oxides of Nitrogen (NOx)	$10,813.78	$254.04	$11,067.82

Road Dust (PM 10)	$3,284.48	$91.77	$3,376.24
Oxides of Sodium (Sox)	$335.36	$9.59	$344.95
Volatile Organic Compounds (VOC)	$389.74	$10.43	$400.17
Total Costs	$15,076.82	$370.79	$15,447.61

Appendix G

OPTIMIZED FULL DEPTH REPLACEMENT SCHEDULE

The first day and shift solely consists of demolition. The crew will consist of 9 workers of which 1 is the foreman, and 8 are the laborers. Within the first shift, the backwall, deck, and parapet body will have been completely demolished by the workers. The backwall will be demolished by 6 laborers using 30-ound pneumatic breakers powered by two air compressor generators. The breaking of the deck will initiate concurrently with the breaking of the backwall, and the breaking will be provided by the skidder. After the skidder is done breaking the deck, the crew assigned with breaking the backwall, after completing their task, will move on to the final breaking of the deck. After the skidder has completed its role in the breaking of the deck header, it will immediately move on to the breaking of the parapet body. During the first shift, torching and cleaning and hand-held excavation will occur when workers are not being used. The first shift tasks, durations and schedule can be seen in Table 109. The demolition is assumed to begin on the same month and day that the case-study began on the 30th of July with demolition beginning at 7:30 AM. The first shift would therefore end on July 30th at 3:39 PM for a duration of 8 hours and 39 minutes.

Table 109: Demolition Tasks Incurred During the First Day and Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time (Hour)	End Time (Hour)
Demo.	1	Sawing	Walk Behind Saw	-	Concrete	Dam	-(-)	0.78	1.00	0.78	6.70	7.48
Demo.	2	Sawing	Handheld Saw	-	Concrete	Parapet Body	1(C)	0.18	1.00	0.18	7.50	7.68
Demo.	3	Breaking	TPB	-	Concrete	Backwall	1(C)	24.87	6.00	37.32	7.50	13.72
Demo.	4	Breaking	Skidder	-	Concrete	Deck	1(C)	2.74	1.00	2.74	7.50	10.24
Demo.	5	Excavating	By Hand	-	Rubble	Dam	3(I)	7.75	2.00	10.98	7.50	12.99
Demo.	6	Torching	Torch	-	Armoring	Dam	4(I)	2.43	1.00	2.43	7.81	10.24
Demo.	7	Breaking	Skidder	-	Concrete	Parapet Body	4(C)	0.07	1.00	0.07	10.24	10.32
Demo.	8	Torching	Torch	-	Rebar	Dam	6(C)	0.50	1.00	0.50	10.24	10.74
Demo.	9	Removing	By Hand	-	Rebar	Parapet Body	8(C)	0.38	1.00	0.38	10.74	11.13
Demo.	10	Breaking	TPB	-	Concrete	Deck	3(C)	7.71	6.00	11.57	13.72	15.65

The second shift, occurring during the first day, consists of demolition, cleaning and construction. The crew will consist of 9 workers, including 2 foremen, 6 laborers, and 1 carpenter. The tasks associated with this shift will pick up where the crew of the first shift left off, and will provide the completion of all tasks leading to placement and positioning of the armoring system, the erection of all of the metal formwork within the deck header, tack welding of the armoring systems to one another, and tack welding of the metal formwork, on the deck side, from the diaphragm to the armoring lip. All demolition, cleaning, and construction tasks included in the second shift are included in Table 110. The second shift, for all of the tasks but the parapet base formwork, would therefore begin on July 30th at 3:39 PM and end on July 30th at 11:39 PM for a duration of 8 hours.

Table 110: Demolition, Cleaning and Construction Tasks Incurred During the First Day and Second Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time (Hour)	End Time (Hour)
Demo.	11	Smoothing	Grinder	-	Diaphragm	Superstructure	10(C)	1.00	2.00	1.22	15.65	16.26
Demo.	12	Smoothing	Grinder	-	Beam	Superstructure	10(C)	0.45	2.00	0.64	15.65	15.97
Demo.	13	Breaking	TPB	-	Concrete	Parapet Base Volume	10(C)	0.88	2.00	1.25	15.65	16.27
Demo.	14	Torching	Torch	-	Metal Formwork	Deck	12(C)	0.50	1.00	0.61	15.97	16.58
Const.	15	Placing	By Hand	Stirrups	-	Parapet Body	13(C)	3.02	1.00	3.02	16.27	19.30
Demo.	16	Torching	Torch	-	Anchorage	Dam	14(C)	0.25	1.00	0.30	16.58	16.88
Const.	17	Drilling	Drill	-	Rebar	Deck	16(C)	7.33	6.00	7.33	16.88	18.10
Cg.	18	Vaccuuming	Vaccuum	-	Drilled Hole Debris	Backwall	17(C)	0.50	1.00	0.50	18.10	18.60
Demo.	19	Removing	Saw	-	Strip Seal	Dam	16(I)	0.02	1.00	0.02	Int	Int
Const.	20	Sawing	Grinder	Rebar	-	Deck	17(C)	2.08	8.00	2.08	18.10	18.36
Const.	21	Positioning	Skidder	-	Armoring System	Dam	20(C)	0.37	1.00	0.37	18.36	18.73
Const.	22	Positioning	By Hand	-	Armoring System	Dam	21(C)	4.13	8.00	4.13	18.73	19.25
Const.	23	Positioning	Skidder	-	Armoring System	Dam	22(C)	0.20	1.00	0.20	19.25	19.45
Const.	24	Positioning	By Hand	-	Armoring System	Dam	23(C)	0.83	8.00	0.83	19.45	19.55
Const.	25	Sawing/ Smoothing	Grinder	Armoring Connection	-	Dam	24(C)	1.37	3.00	1.37	19.55	20.01
Const.	26	Drilling	Drill	-	Armoring System Support	Dam	25(C)	0.37	6.00	0.52	20.01	20.09
Const.	27	Drilling	Drill	Anchorage	Abutment Seat	Backwall	26(C)	1.98	5.00	2.81	20.09	20.65
Const.	28	Sawing	Saw	Wood	Formwork	Backwall	27(C)	1.40	1.00	1.40	20.65	22.06
Const.	29	Sawing	Grinder	Metal	Formwork	Deck	27(C)	8.77	6.00	8.77	20.65	22.12
Const.	30	Placing	By Hand	Wood	Formwork	Backwall/ Dam	28(I)	5.15	2.00	5.15	20.65	23.23
Const.	31	Placing	Saw	Wood	Formwork (Blockout)	Parapet Base	26(C)	3.93	1.00	3.93	20.65	24.59
Const.	32	Tack Welding	Engine Driven Welder	Welding Stick Electrodes	Metal Formwork+ Armoring+ Anchorage (Deck)	Dam	29(C)	1.53	1.00	1.53	22.12	23.65

The third shift, occurring during the second day, consists solely of construction. The crew will consist of 9 workers, including 1 foreman and 7 laborers and 1 carpenter. The tasks associated with this shift will pick up where the crew of the second shift left off, and will provide the completion of all tasks leading to the completion of all formwork in the dam and parapet body, the placement of all steel reinforcement, preperations for the pouring of concrete, the pouring of concrete within the dam and total parapet base and body and all associated curing applications. All demolition, cleaning, and construction tasks included in the third shift are included in Table 111. The third shift, for all of the tasks, but the curing of wet concrete incurred, would therefore begin on August 1st at 12:35 AM and end on August 1st at 5:40 AM for a duration of 5 hours and 5 minutes.

Table 111: Demolition, Cleaning and Construction Tasks Incurred During the Second Day and Third Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time(Hour)	End Time (Hour)
Const.	33	Placing	Drill/ Saw	Wood	Formwork	Parapet Body	31(C)	15.10	9.00	15.10	24.59	26.27
Const.	34	Spraying	By Hand	Insulating Foam Sealant	Formwork	Parapet Body	33(C)	0.18	1.00	0.18	26.27	26.44
Const.	35	Placing	By Hand	Anchorage	Abutment Seat	Backwall	32(C)	1.50	3.00	2.13	23.65	24.36
Const.	36	Placing	By Hand	Rebar+Stirrups	-	Deck	35(C)	16.12	6.00	19.61	24.36	27.63
Const.	37	Placing	By Hand	Cork	Formwork	Backwall	35(C)	1.67	3.00	2.03	24.36	25.03
Const.	38	Placing	By Hand	Rebar	-	Backwall	37(C)	4.70	3.00	6.19	25.03	27.10
Const.	39	Placing	Saw	Wood	Formwork (Blockout)	Backwall	38(C)	0.33	4.00	0.47	27.10	27.21
Const.	40	Placing	Saw	Wood	Formwork (Blockout)	Deck	36(C)	1.42	4.00	2.01	27.63	28.13
Const.	41	Spraying	By Hand	Concrete Adhesive	-	Dam and Pp Base	34,39,40(C)	0.07	1.00	0.07	28.13	28.20
Const.	42	Vibrating	Vibrator	-	Wet Concrete	Dam and Pp	41(C)	0.50	1.00	0.50	28.20	28.70
Const.	43	Shoveling	By Hand	Wet Concrete	-	Dam and Pp	41(C)	1.00	1.00	1.00	28.20	29.20
Const.	44	Smoothing	By Hand	-	Wet Concrete	Dam and Pp Body	42,43(C)	2.06	9.00	2.06	29.20	29.43
Const.	45	Spraying	By Hand	Curing Compound	Wet Concrete	Dam and Pp Body	44(C)	0.05	1.00	0.05	29.43	29.48
Const.	46	Placing	By Hand	Burlap	Wet Concrete	Dam	45(C)	0.06	1.00	0.06	29.48	29.54
Const.	47	Placing	By Hand	Weeper Hose	Wet Concrete	Dam	46(C)	0.06	1.00	0.06	29.54	29.61
Const.	48	Placing	By Hand	Tarp	Wet Concrete	Dam	47(C)	0.06	1.00	0.06	29.61	29.67
Crng.	49	Curing of Concrete	-	-	Wet Concrete	-	47(C)	72.00	1.00	72.00	29.67	101.67

Days 3 and 4 consist of the curing durations for the wet concrete. It is recommended that other operations be provided on the field to compensate for the durations at which lanes are closed. The fourth shift, occurring during the fifth day, will consist of 3 workers, including 1 foreman and 2 laborers. The fourth shift will consist of smoothing of all newly poured concrete components with grinders, the application of the backer rod, primer, and silicone to the parapet and approach/header interface and the application of the aforesaid applicants to the backwall, in the same order, sandblasting. Table 112 provides the tasks and schedule associated with the beginning of the fourth shift up to the placement of the seal between the armoring. The fourth shift, during the fifth day, will begin at 5:40 AM and end at 1:25 PM, for a duration of 7 hours and 45 minutes.

Table 112: Cleaning and Construction Tasks Incurred During the Fifth Day and Fourth Shift (Last Day and Shift) Excluding Seal Implementation

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time (Hour)	End Time (Hour)
Const.	50	Grinding	Grinder	Cork	Formwork	Backwall	49(C)	0.21	1.00	0.21	101.67	101.88
Cg.	51	Smoothing	Grinder	-	Concrete	Dam and Pp Body	49(C)	2.05	2.00	2.05	101.67	102.69
Const.	52	Placing	By Hand	Backer Rod	-	Approach/Pp Interface	49(C)	0.28	1.00	0.28	101.67	101.95
Const.	53	Applying	By Hand	Primer	-	Approach/Pp/BW Interface	52(C)	0.10	1.00	0.10	101.95	102.05
Const.	54	Pouring	AT 1200 S	Silicone	-	Approach/Pp/BW Interface	53(C)	0.31	1.00	0.31	102.05	102.36
Crng.	55	Curing of Silicone	-	-	Wet Silicone	-	54(C)	0.15	1.00	0.15	102.36	102.51
Const.	56	Applying	By Hand	Methacrylate	-	Approach/Pp/BW Interface	55(C)	0.16	1.00	0.16	102.51	102.67
Crng.	57	Curing of Methacrylate	-	-	Wet Methacrylate	-	56(C)	6.00	1.00	6.00	102.67	108.67
Cg.	58	Sandblasting	Sandblaster	-	Rubble	All	57(C)	0.75	1.00	0.75	108.67	109.42

The duration of the fifth shift, and subsequently the duration of Phase 1, will differ based on the type of seal chosen as explained in the partial depth and sealant replacement section. The fifth shift will consist of 4 workers, 1 of which is the foreman and 2 of which are laborers and 1 of which is the carpenter, regardless of the sealant chosen. It is recommended that 4 of the workers be kept from the fourth shift or that the workers laboring under Phase 2 supplement the 4 workers of the fourth shift at a later time, to reduce overhead for the owner. If a strip seal is implemented between the armoring, Phase 1 will conclude at 5:03 PM, for a shift duration of 3 hours and 38 minutes and a phase duration of 4 days and 11 hours and 38 minutes. Table 113 provides the implementation of the strip seal between the armoring and the final airblasting treatment. The strip seal once implemented into the armoring, though an adhesive is used, can incur traffic as soon as it is implemented.

Table 113: Strip Seal Implementation and Airblasting During the Fifth Day and Fourth Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time (Hour)	End Time (Hour)
Const.	59	Placing	By Hand	Strip Seal Extrusion	Armoring	Dam	57(C)	10.92	3.00	3.64	109.42	113.06
Cg.	60	Airblasting	Airblaster	0.00	Debris	All	58(C)	1.02	1.00	1.02	109.42	110.44

Table 114 provides the implementation of the open compression seal between the armoring and the final airblasting treatment, including its associated 2-hour curing period. As aforementioned, due to the duration associated with the implementation and curing of the V-Seal, and its short life expectancy, it will no longer be considered. If an open cell compression seal is implemented, Phase 1 will conclude at 3:55 PM, for a shift duration of 2 hours and 30 minutes and a phase duration of 4 days and 10 hours and 30 minutes, 1 hour and 8 minutes faster than the implementation of the strip seal.

Table 114: Open Compression Seal Implementation and Airblasting During the Fifth Day and Fourth Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (WHr)	Start Time (Hour)	End Time (Hour)
Const.	59	Placing	By Hand	Compression Seal	Armoring	Dam	57(C)	1.50	3.00	0.50	109.42	109.92
Cg.	60	Airblasting	Airblaster	-	Debris	All	58(C)	1.02	1.00	1.02	109.42	110.44
Crng.	61	Curing of Adhesive	-	-	Wet Adhesive	-	60(C)	2.00	-	2.00	109.92	111.92

Table 115 provides all subsequent tasks that would occur intermittently throughout the duration of the phase. It was determined that the values would not be able to fit into the schedule as they did not occur specifically within one-time period or stage from initiation to completion. The values in Table 115 were re-simulated to occur in one day, with a fixed crew of 4 workers, of which 3 are laborers and 1 is the foreman. Such costs will be inconsequential to the road user costs as they are assumed to occur within the phase; the tasks provided in Table 115 will only affect the owner, and environmental costs due to extra hours worked and operating power sources.

Table 115: Intermittent Cleaning Tasks Incurred Throughout the Duration of the Project

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (WHr)	Workers	Expected Duration (Hr)	Start Time (Hour)	End Time (Hour)
Cg.	61	Airblasting	Airblaster	0.00	Debris	Dam	()	1.60	1.00	1.60	7.50	9.10
Cg.	62	Collecting	By Hand	0.00	Rubble	Dam	()	19.54	3.00	6.51	7.50	14.01
Cg.	63	Collecting	Skidder	0.00	Rubble	Dam	()	3.48	1.00	3.48	9.10	12.58
Cg.	64	Sandblasting	Sandblaster	0.00	Rubble	Dam	()	0.67	1.00	0.67	12.58	13.25
Cg.	65	Collecting	By Hand	0.00	Rubble	Parapet Body	()	0.48	1.00	0.48	13.25	13.72