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Bridge Retrofit or Replacement Decisions: Tools to Assess Sustainability and Aid Decision-Making

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16. 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 decision on the economy, environment, and society. Bridge management sustainability assessment can be thought of as impacting owners (A), road users (B), and the environment (C). The development of life cycle inventories that cost sustainability impacts are increasingly relevant to bridge management systems (BMS).

This research proposes an A+B+C costing method to assess sustainability impacts that are otherwise externalized. Employing the A+B+C costing method, the impacts incurred to the owner, user, and environment and are summed to provide a total cost to score the overall efficiency and sustainability of each option. Transportation agencies spend millions of dollars to maintain rehabilitate, and replace bridge expansion joints each year. A case study measured the sustainability impacts of different deck expansion joint rehabilitation/replacement options for a bridge's remaining service life using the A+B+C costing method. The most cost effective joint maintenance program for the remaining life of the bridge was found to be approximately $ 188,000. The most expensive joint maintenance program cost approximately 52 % more. For each program option considered – the owner costs ranged between 10-15 %, the societal costs ranged between 80-90 %, while the environmental costs ranged between 2.6 and 2.7 % – of the total.

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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; these impacts result in costs but bridge owners do not measure or pay those costs directly. Bridge management sustainability assessment quantifies the impacts to the economy, society, and environment by considering impacts to 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 life-cycle inventories (LCI) 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 sustainability assessment in decision-making can improve 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 project work. The manner in which time is given a monetary value depends on the agency and can consider road user and vehicle operating costs. However, traditionally, the costs incurred to society, specifically road users, through travel delays and increased vehicle operation costs are disregarded. In addition, the environmental costs to human health from pollutant emissions, recognized as “C” costs, are ignored.

By incorporating the costs incurred to users and the environment, both efficient and sustainable practices can be incentivized for contractors throughout bidding and project implementation. A+B+C costs vary between different BMS maintenance, rehabilitation, and replacement operations and by how traffic flows change with the work zone as compared to normal traffic patterns. Knowledge of A+B+C costs can help contractors choose the most sustainable or lowest sustainability impact cost option when bidding or carrying out a project. Assessing sustainability impact costs before starting a project can influence contractor decisions on how to plan the schedule of operations for BMS maintenance, rehabilitation, and replacement with regards to how it impacts road users through traffic flow changes.

For this research, we investigated various maintenance, rehabilitation and replacement actions that are pivotal to the structural health of a bridge. A case study measured the sustainability impacts of different deck expansion joint rehabilitation/replacement options in the units of dollars. Thus, sustainability 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. The most expensive joint maintenance program would cost approximately $285,000, approximately 52% more expensive than the optimal 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, focused solely on air emissions, amounted to approximately 3% of the total costs. The societal costs from joint maintenance are large however the environmental costs are also likely underestimated since emissions and impacts to water and soil were not considered.

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: more frequent joint inspection 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." Additionally, the agencies identified the need for life cycle cost analysis 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.

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

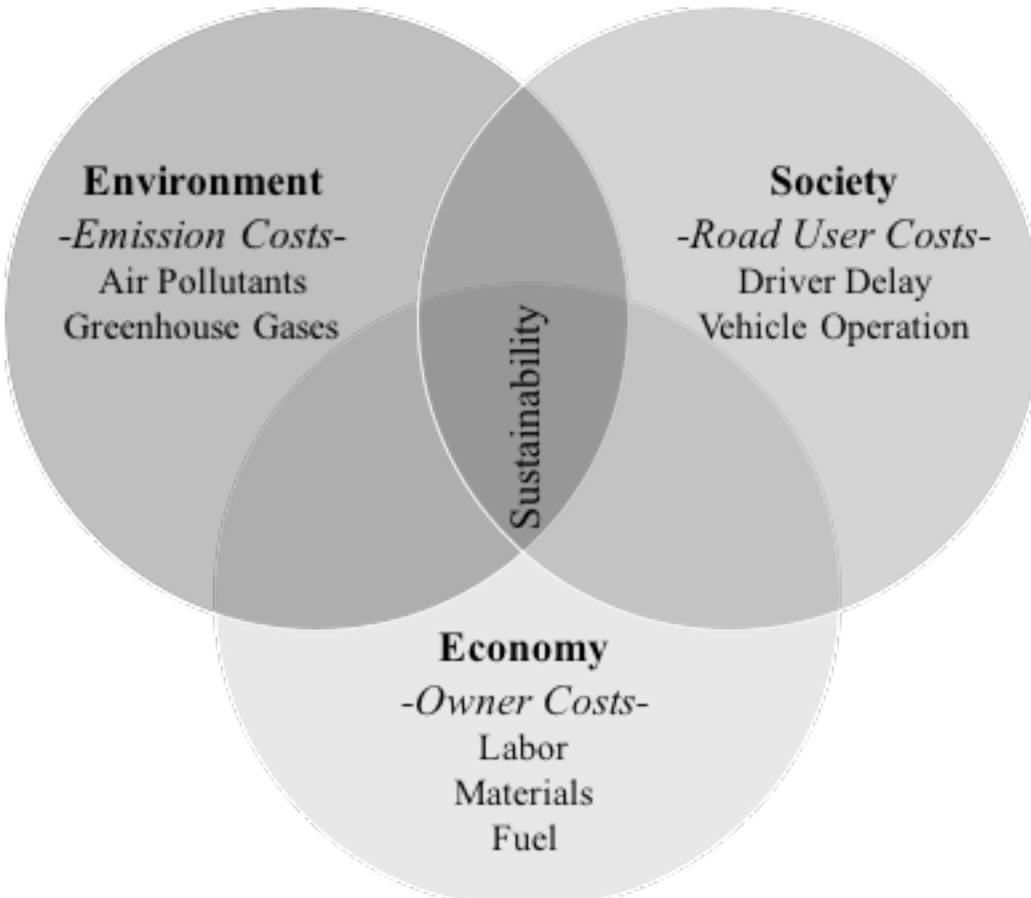


Figure 1: The "Triple Bottom Line" for Bridge Repair

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 through lane closures and detours. The cost to the environment was determined by the amount of criteria pollutants emissions (by weight) from tools used for joint rehabilitation and increased emissions due to the presence of a work zone. These emission weights were multiplied by cost factors to calculate a total environmental cost.

1.2 Terminology

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	Apportioning resources in a system.
Applicant	Applicant is the material upon which a task and tool act. This is used to determine effective work duration during construction activities.
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 (Bw)	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 Component	General Designation of Task Occurrence Location
Bridge Deck	One component of the bridge's superstructure which is the roadway of the bridge.
Bridge Superstructure	The components of a bridge that support the deck, which carries the live load, and provide a load path to the substructure.
By Hand	Indicates the usage a of non-motorized instrument as the tool designation in completing the task
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Commercial Travel	Designates travel in a vehicle for business purposes.
Component's Element	The specific location within the location, or entity, of the bridge component in question
Consumable Task Duration (Cnsmbl)	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 daily, binary.
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 from a detour.
Detour Delay Time	The time lost to users through the usage of a roadway, specifically from a detour.
Detour (Bypass)	A route intended to circumvent an 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 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.
Excavating	Demolition-Shoveling demolished or soft concrete "By Hand"
Fascia	The outermost edge of a particular bridge component.
Free Direction	The direction of a roadway that is not completely obstructed from vehicular volume.
ft	Linear foot
ft^2	Square foot
ft^3	Cubic foot
Greenhouse Gas	A gas that absorbs infrared radiation.
Grout	A viscous cement based liquid that serves as an adhesive and filler.
Handheld Saw	Self-powered, handheld concrete saw for intermittent, shallow concrete sawing during in field operations
Header	The portion of the blockout that includes the backwall, deck, or any other entity.
Idle or Idling	Time spent doing nothing.
Index	The order at which tasks were completed on the field
Index Dependencies	Specifies whether the preceding task must be completed (C) or can go on intermittently (I) for the task of interest to finish.

Joint	A component of the bridge that allows for structures to expand and shrink, while providing a smooth transition between structures.
Life Cycle Assessment (LCA)	A systematic approach in determining the environmental impacts from material and energy flows that occur throughout the development of a product, or the completion of a task, from cradle to grave.
Life Cycle Inventory (LCI)	A database that determines the material and energy flows used to calculate the environmental impact associated with a LCA.
Median	A divider between opposing directions on a roadway
Methacrylate	A bonding agent and a sealant.
MR&R	Maintenance, repair, and rehabilitation
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.
NO_X	Nitrogen oxides
Owner	The entity that owns the bridge. This may be different from the agency that maintains and represents the bridge.
Parapet (Pp)	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.
PM_{10}	Particulate Matter of a diameter less than or equal to 10 micrometers in diameter
Pound (lb)	Unit of weight

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 and vehicle operating costs.
Silicone	Material used as a gap filler during the construction phase.
Skidder	Skid Steer Loader
SO_X	Sulfur oxides
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.
Steel Reinforcement	Armoring System [Anchorage (welded and bolted), Armoring, Brackets] and Rebar
Structure	Bridge
Task	A certain action undertaken.
Through Traffic	A certain direction of traffic that is traversing the structure.
Tool	Equipment with which tasks were completed
Torch	Tool connected to Oxygen and Acetylene Tanks, tasked with Performing Torch/Heat Cutting
Traffic Pattern Group (TPG)	Roadways that are categorized based on their function by the Delaware Department of Transportation.
Traveler Delay Cost	Excess cost to users due to delay of travel on 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 or acceleration.
Users	Those that use certain roadways and are subject to its effects.
Vehicle Operating Cost	The costs incurred to vehicle owners through upkeep and maintenance of the vehicle itself.

Vehicle	An automobile or freight truck.
VOC	Volaticle Organic Compounds
Wage	Earnings paid 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 paid 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.
Worker-hour (W-hr)	An hour of labor by one worker
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 such as social and environmental impacts.

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

- 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 option.

- 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 operations for bridge joint replacements. 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.

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.

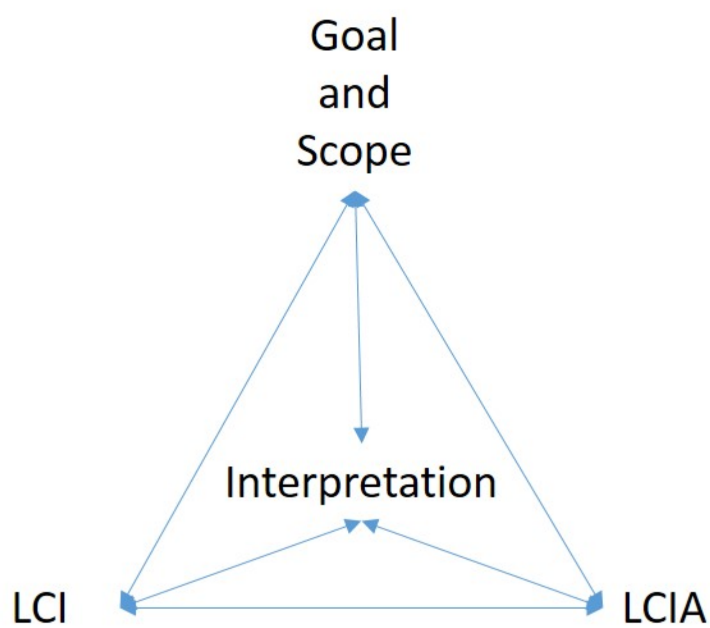


Figure 2: LCA Stages (Recreated from Zimoch, 2012)

Goal and 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 system boundary and functional unit.

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. All transportation activities are included between life cycle stages as well. 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 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.

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 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. This research considered the functional unit of joint use over the expected remaining bridge lifetime. Over the life of a bridge joints will potentially require maintenance and reconstruction or replacement multiple times. Replacement of a bridge joint involves many different operations on specific bridge components. Thus fuel and material use were compared on a per unit basis to the relevant component of the bridge, e.g. square foot of concrete demolition. The information gathered from the case study can then be used to simulate relatively similar steps (at varying scales) of other joint reconstruction operations. Collecting information in this way provides the initial steps to simulate the owner, user and environmental costs associated with different joint replacement options over a bridge's lifetime.

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, 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. This research considers impacts over two analysis periods; the replacement of all joints at the current bridge condition and the joint replacements needed over the expected remaining bridge lifetime.

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 are not subject to change may be 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: Bridge Life Cycle Stage Considerations (Harvey et al., 2010)

<table>
<tr><th>Production Stage (Material Extraction and Production Stage)</th><th>Implementation Stage (Construction/Rehabilitation and Maintenance Stage)</th><th>Use Stage</th><th>End-of-Life Stage (EOL)</th></tr>
<tr><td rowspan="8">Raw material acquisition (Excavation and refining may be subject to cut-off)</td><td>Transportation to the site for all materials and equipment that is to be utilized in order to complete this Stage</td><td>Additional consumption of fuel due to bridge deck deterioration due to</td><td rowspan="8">Material can either be recycled or landfilled</td></tr>
<tr><td>Distance covered to transport material</td><td>Fuel economy of vehicles traveling on deteriorated deck</td></tr>
<tr><td rowspan="6">Fuel emissions of transporting vehicles</td><td>Damage to freight</td></tr>
<tr><td>Tire wear</td></tr>
<tr><td>Construction/rehabilitation traffic</td></tr>
<tr><td>Traffic growth</td></tr>
<tr><td>Traffic size and rate of traffic size change</td></tr>
<tr><td>Speed Distribution</td></tr>
<tr><td rowspan="5">Raw material production</td><td>The manufacturing and utilization of all tools used</td><td>Fuel consumption due to varying types of maintenance</td><td rowspan="5">Emissions and fuel used to demolish the site must be considered</td></tr>
<tr><td>Hour of mechanical tool usage</td><td>Construction/rehabilitation traffic</td></tr>
<tr><td rowspan="4">Associated fuel emissions of tool usage

Water transport to site</td><td>Traffic growth</td></tr>
<tr><td>Traffic size and rate of traffic size change</td></tr>
<tr><td rowspan="3">Speed Distribution

Roadway lighting</td></tr>
<tr><td rowspan="2">Feedstock energy of producing materials (Oil refining may be subject to cut-off)</td><td rowspan="10">Consideration of the amount of emissions and usage of fuel and resources order to allocate remnants of site to either recycling locations or to landfills</td></tr>
<tr><td>Volume of water used</td></tr>
<tr><td rowspan="6">Technology and Equipment utilization in material production (This step may be subject to cut-off)</td><td>Emissions and fuel consumption by vehicles in construction</td><td rowspan="8">Water pollution from runoff</td></tr>
<tr><td>Type of traffic that is in queue</td></tr>
<tr><td>Speed Distribution</td></tr>
<tr><td>Traffic size and rate of traffic size change</td></tr>
<tr><td>Predicted emission standards</td></tr>
<tr><td></td></tr>
<tr><td rowspan="2">Transportation of all materials at all stages in material production Stage.</td><td>Consumed energy for lighting and implementation of signs</td></tr>
<tr><td>Temporary Infrastructure</td></tr>
</table>

Impact Assessment

The life cycle impact assessment (LCIA) utilizes the data provided in the LCI to evaluate the impacts 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 damage potential from global warming from the amount of CO2 and methane emissions (Harvey et al., 2010). One approach is to convert all impact categories into a single score to allow comparison of all different impacts with common units such as converting the impacts of global warming to human health and ecological damage to costs (Harvey et al., 2010).

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, and 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).

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 sensitivity 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 (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 to the agency, including all necessary repair and maintenance expenditures over a specified time period (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 regular intervals 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). Life cycle bridge performance characterization involves using probabilistic bridge deterioration models in conjunction with environmental impact assessment to inform life cycle costing (Sun et al., 2015). User costs will likely dominate LCCA-informed bridge repair and replacement decisions even though further research on quantifying impacts to users during repair and maintenance operations is needed (Thoft-Christensen, 2012). Due to the current lack of, or uncertainty in, data about the environmental and user impacts of the variety of bridge management strategies and associated practices (Sun et al., 2015; Thoft-Christensen, 2012), 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.

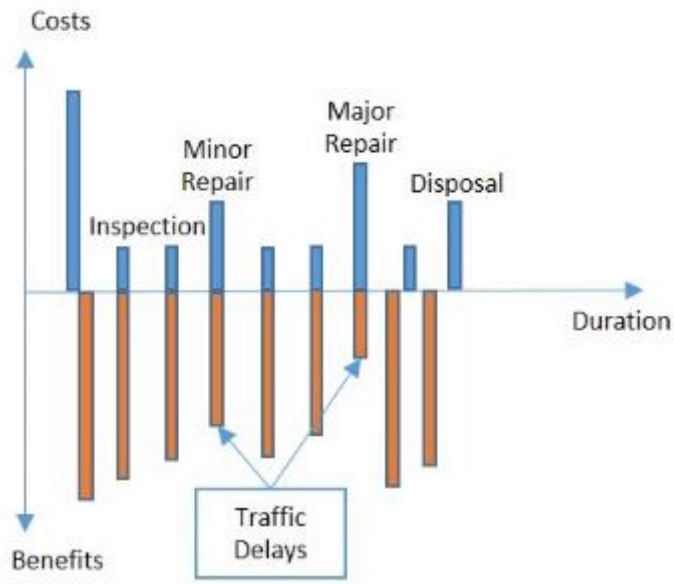


Figure 3: User and Agency Costs (Recreated from Troive, 1998)

In addition to costs to users, costs to society are incurred and considered in a combined LCA-LCCA as depicted in Figure 4. In this model, environmental costs are considered a part of societal costs whereas user costs are considered on their own. Considering the environment as a separate stakeholder has been met with skepticism that concerns are already met through consideration of other stakeholders (Phillips & Reichart, 2000). Arguably the environment can be considered as a standalone stakeholder, especially with regards to climate change concerns (Haigh & Griffiths, 2009), which is the approach taken in this research. Furthermore, road users are a part of society, and in this research are considered under societal costs. Accident cost estimation is highly variable (Blincoe, Miller, Zaloshnja, & Lawrence, 2015) and for that reason were not considered in this research.

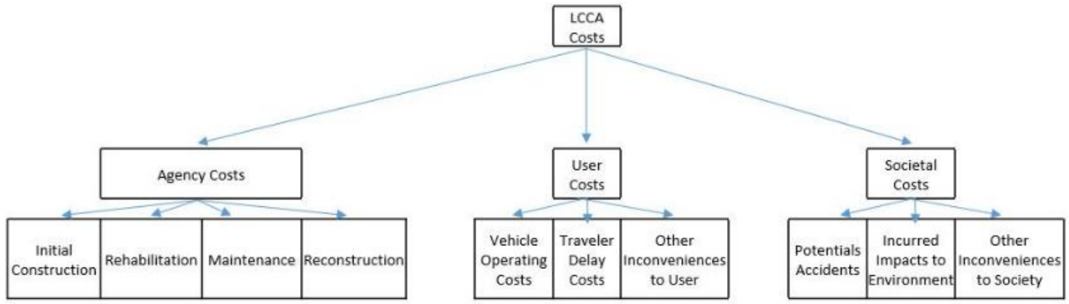


Figure 4: Combined LCA-LCCA Cost Framework (Recreated from Ozbay et al., 2003)

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).

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 for federally funded projects (Office of Management and Budget, 2005).

How to discount environmental impacts is more difficult than simply 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 are associated with a degree of uncertainty; when employing multiple discount rates, it is a concern that such uncertainties would be compounded. Although the discount rates can affect the overall cost of a project notably, they are not considered in this research, the reason being that there is no agreement by experts on what that rate should be. Moreover, some argue whether a discount rate should be applied at all.

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 use and wages. User costs consist of user delay and vehicle operating costs. Environmental costs are due to the increase in driving from detours 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 maintenance and repair (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 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. Societal costs for joint replacement operations and BMS in general are discussed. Ultimately in this research passenger delay and increased vehicle operating costs are considered as societal costs.

The American Association of State Highway and Transportation Officials' "User and non-user benefit analysis for highways" or Redbook provides comprehensive guidance on how to assess impacts and benefits to society from roadway improvements (AASHTO, 2010). 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 (measured in dollars) 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.

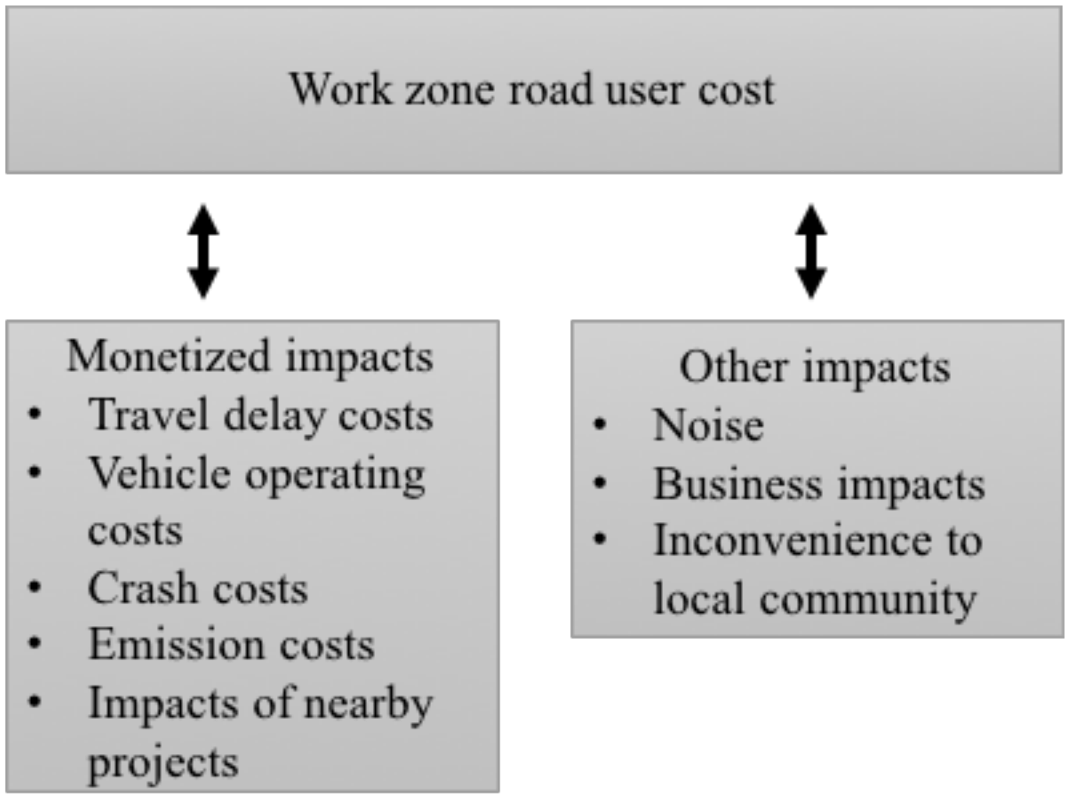


Figure 5: Work zone User Costs (Mallela & Sadavisam, 2011)

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. 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. 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.

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 (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, stages of the operation and thus work zone and lane closure changes 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, knowing the effect of detours, vehicle types, occupancy of said vehicle types, and the work zone set-up is imperative.

The methods presented by ETSI Stage 1 in determining the driver delay costs, expand upon the factors presented by the BridgeLCC software by taking into account the variations in valuing time based on considering the number of commercial vehicles and differences in their associated costing factors. The method provided by ETSI also acknowledges the effects to other roadways nearby the work zone.

The ETSI approach 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 and neglects impacts to passengers inside the vehicles.

The ETSI approach neglects a variety of factors;

- traffic speed during roadwork,
- traffic speed during normal conditions by time of day,
- the number of passengers within each vehicle type, 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. 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).

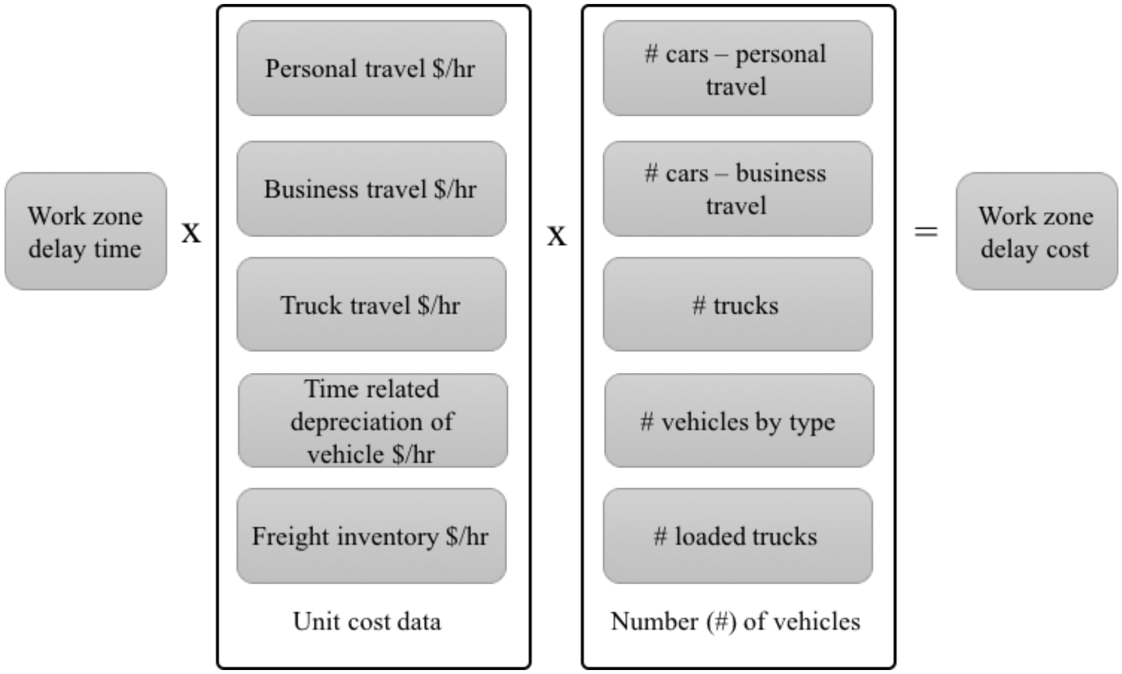


Figure 6: Necessary constituents in determining total work zone travel delay costs (Mallela & Sadavisam, 2011)

In determining the traveler delay costs, the monetized value of time must be determined. Specifically, the monetized value of time for passengers and drivers in automobiles traveling for both personal and business reasons must be accounted for as must passengers and drivers traveling in both freight and truck vehicles. The total monetary value of travel time is the sum of the lost delay time incurred to drivers 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, 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 drivers 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 drivers 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 number of passengers in a vehicle affects the number of people that experience travel delay time. 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 drivers 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 travel and detour delay times are determined can travel delay costs and detour delay costs can be determined for automobiles and freight vehicles.

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 and normal conditions,
- The number of commercial traffic vehicles and how it varies throughout the duration of the project, and
- The manner at which speed varies before and during the work zone on the structure and detours.

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).

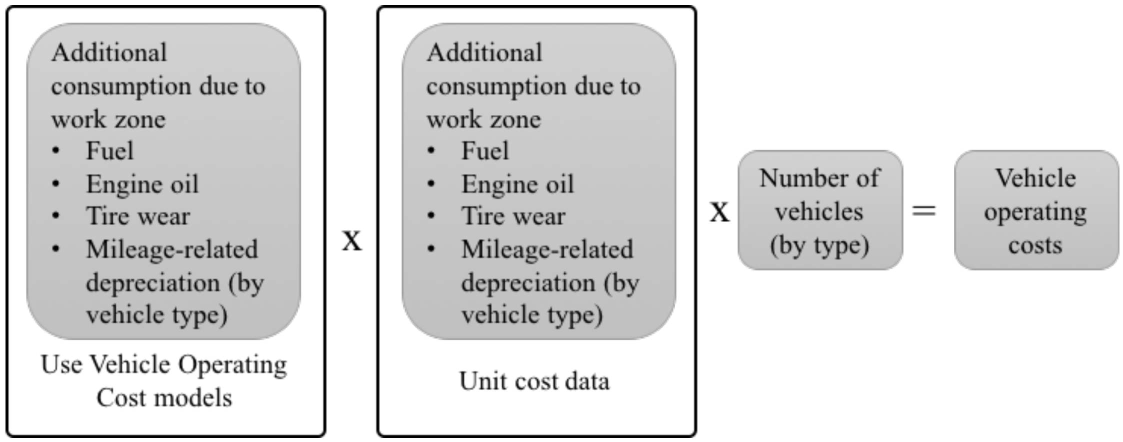


Figure 7: Vehicle Operating Cost Components (Mallela & Sadavisam, 2011)

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" in the 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 additional distance of 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 per vehicle operating mile. Estimates have been found for small, medium, and large sedans, four-wheel drive sport utility vehicles, and minivans. 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 per operating vehicle operating mile as can be seen in Table 5.

Table 5: Truck Vehicle Operating Costs in dollars (Trego & Murray, 2010)

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 FHWA provides average vehicle operating costs that include depreciation factors as seen in Table 6 (Mallela & Sadavisam, 2011).

Table 6: FHWA Vehicle Operating Costs in dollars (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	23.3	24.64	26.23	26.25	25.31	46.8

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 are provided in Appendix E.1 and E.2, respectively, with supplementary commentary.

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)" 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 (Blincoe, Miller, Zaloshnja, & Lawrence, 2015). According to Section 2 of the "New Jersey Department of Transportation (NJDOT) Road User Cost Manual", NJDOT 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 data and thus crash costs cannot be implemented into a road user cost study ("NJDOT Road User Cost Manual," 2015). Although such costs are not considered this would be an area to consider for future research and 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). Also data on environmental impact of bridge maintenance and repair actions is very limited, more is needed (Sun et al. 2015). Kendall, Keoleian, and Helfand's LCA model (2008) defined environmental costs as those produced by pollution damages. The costs resulting from climate change create a variety of economic impacts such as damage to human health through increased exposure to tropical diseases. These damages have been given monetary value by various researchers (Mallela & Sadavisam, 2011).

The EPA tracks the levels and damage of six criteria air pollutants for National Ambient Air Quality Standards per the Clean Air Act – ground level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, nitrogen dioxide. In addition the EPA regulates carbon polluting agents such as carbon dioxide for power plants (U.S. Environmental Protection Agency (EPA) 2015). Currently the EPA has created greenhouse gas standards for heavy-duty trucks starting in 2021 in partnership with the U.S. DOT's National Highway Traffic Safety Administration and in consultation with the State of California's Air Resources Board (Clair and Thomas 2016).

The emissions of equipment used in the field were modeled by EPA Motor vehicle emissions simulator (MOVES) software to obtain emissions of atmospheric carbon dioxide (CO2), carbon monoxide (CO), fine particulate matter (PM 2.5), nitrogen oxides (NOx), road dust (PM 10), sulfur dioxide (SO2), and volatile organic compounds (VOC) per the amount of time the equipment was operated. Information about equipment used in the field of a similar engine size (in horsepower) was used from the Nonroad database in MOVES to find emissions rates of the emission types listed above. The costs per metric ton of the emitted chemicals from CALTRANS (California DOT) EMFAC model were multiplied by the total weight of emissions for each piece of equipment (Mallela & Sadavisam, 2011).

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). Emission rates for all EPA criteria pollutants were not found for all emission generators and activities that occurred during the case study; specifically, the engine driven welder lacked values for idling emissions. Missing emissions values for equipment activities (such as welder idling) or emission types (such as EPA criteria pollutants lead and ozone) would have to be found elsewhere and scaled with the costing factors from the CALTRANS EMFAC model.

There are two types of models that can be used to determine emission factors from vehicles - static or dynamic models (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 (grams/mile)					Trucks (grams/mile)				
	CO	NO_X	PM10	SO_X	VOC	CO	NO_X	PM10	SO_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 assist bridge owners in prioritizing bridge maintenance work. This means selecting and performing appropriate work for a bridge at the right point in time and cost-effectively (FHWA, 2016). 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 construction specifically structure replacement or major rehabilitation.

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). 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 (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 VDOT has suggested the following prioritization of funding:

- Preventive Maintenance – 15%,

- Painting – 10%,

- Restorative Maintenance – 25%, and

- Rehabilitation/Small Structure Replacement – 50% ("VDOT Maintenance and Repair Manual," 2014).

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 (PM) 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 include:

- Sealing of leaking joints,
- Replacement of leaking joints,
- Installation of deck overlays,
- Installation of cathodic protection systems, and
- Complete, spot, or zone painting/coating of steel structural elements (Ahmad, 2011).

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 from VDOT. 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 10: Preventive Maintenance Activities According to the VDOT ("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.

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

Rehabilitation

VDOT guidelines state that 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 need 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 100 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: the final sufficiency rating (SR) is the sum of S1 through S4 (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 removes those aspects that increase deficiencies 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).

Replacement

VDOT guidelines state that 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. 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, transportation agencies 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. The insufficient frequency of joint maintenance and lack of information regarding joint life expectancies and costs impact BMSs (Purvis, 2003). A life cycle inventory is applicable and imperative to adding knowledge about joint replacement within BMSs to help predict overall costs. Joints are usually inspected every two years (when the bridge itself is inspected).

There is an array of differing joint types, including open and closed, joint sealants. Joints are usually over expansion bearings, or expansion joints, and accommodate deck movements, i.e. expansion, contraction, and rotation of the bridge deck. 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. Closed joints are designed 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. The joint armor and its anchorage system, being made of steel, are also susceptible to corrosion. One side of each individual armor is on the riding surface of the deck. 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;

- 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 Northeast Bridge Preservation Partnership (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 showed that many DOTs use 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 report, were juxtaposed by those from various developers including WBA; it was concluded that the deck displacement ranges did not differ by a significant amount from the manufacturer's specifications.

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.

Compression Seals

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). The compression seal is collinear with the upper most surface of the roadway, though the top of the seal should be beneath the roadway.

Compression seals are generally regarded as exhibiting good performance for sealing deck joints. 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). Due to deck movement, initial implementation of the compression seal necessitates that the joint opening be sized so that expansion and contraction does not remove the sealant from the deck surface or crush the sealant. Compression seals are easy and fast to remove and replace in a damaged region. A portion (that can be properly spliced) can be removed and, after the joint is cleaned, replaced with a new adhesive. Thus premolded sealant reduces operating costs and traffic closures.

Though some transportation agencies prefer CS, concerns with this system claiming include that such sealants are not dependable as they exhibit a short service life due to fragility and 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: the reliability of one type of cell over the other is debatable (Purvis, 2003). Internally, an open compression seal or open cell compression seal is porous and has vertical and diagonal neoprene threads as shown in Figure 8. The open compression seal is continuous with its versatility uncommon amongst most other premolded sealants. 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. Of Northeastern transportation agency respondents, approximately 33% of them use CS systems during new construction and approximately 44% use CSs during rehabilitation and replacement actions (Milner & Shenton III, 2014). Of all of the closed joints employed in the Northeast, the most common closed joint system that is becoming discontinued is the compression seal joints.

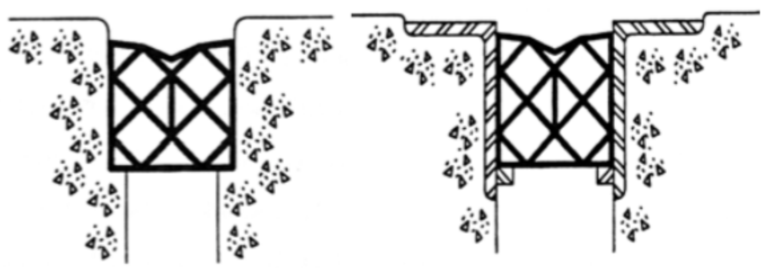


Figure 8: A Typical Open Cell Compression Seal (Purvis, 2003)

Closed cell compression seals, though denser than open compression seals, are still considered to be low density (Figure 9). CCF joints applied during new construction and those applied during rehabilitation/replacement experience 5 and 2 years of service life, respectively. Of Northeastern transportation 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 (Milner & Shenton III, 2014). Both open cell and closed cell seal types must be sized to fill the available joint opening. Maintenance is provided to the compression seal by sweeping and flushing the joint. Inspection is done of the seal, armor, keeper bar and all other metallic surfaces for cracks and weathering (Taavoni & Tice, 2012).

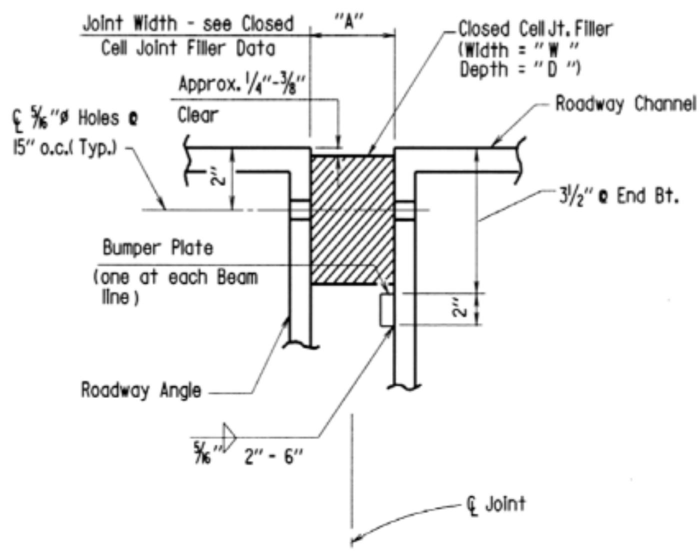


Figure 9: A Typical Closed Cell Compression Seal (Purvis, 2003)

Strip Seals

Strip Seals (SS) (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 are regarded by responding agencies 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 deck displacement (Taavoni & Tice, 2012). Membrane seals, however, are susceptible to tearing (Taavoni & Tice, 2012). Thus, it is important that the cross sectional area is made uniform or the seal is sized to compensate for changes in cross sectional area, or obstructions (such as gutter lines), along the joint. 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 the edges of the joint, replacing the membrane, and inspecting the joint face armor for deterioration and corrosion.

SS joints applied during new construction and those applied during rehabilitation/replacement actions experience 15 and 10 years of service life, respectively. Of responding DOTs, 100% of them used strip seals for both implementation during new construction and during rehabilitation and replacement actions (Milner & Shenton III, 2014).

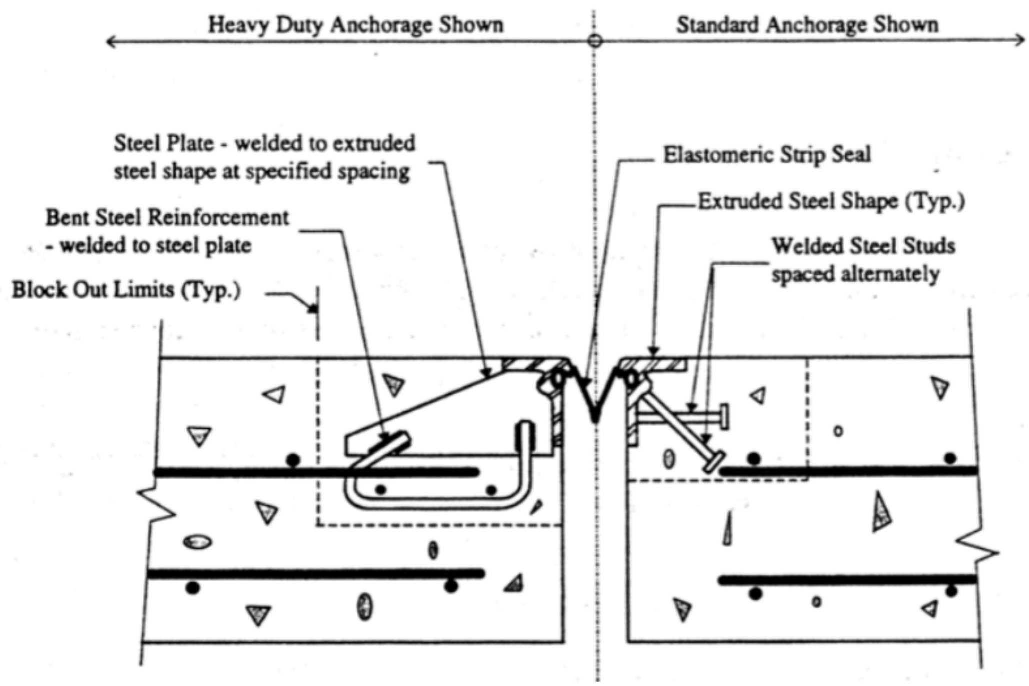


Figure 10: A Strip Seal Joint (Purvis, 2003)

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 are chemically designed to be more elastic (Milner & Shenton III, 2014). APJs 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. The most popular application of the plug joint is with a waterproof membrane 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 pushed into the joint as well. The premolded filler binds to its surrounding joint surfaces and create a truly watertight seal after a polymer-modified asphalt binder material is poured on top of the backer rod (Purvis, 2003). The asphalt binder is heated 370 degrees Fahrenheit. After the material is poured, a steel plate, referred to as the gap plate at 20 cm (8 inches) wide, is placed on top of the joint crevice partially covering both top sides of the blockout. The blockout/gap plate surface is then covered and the joint is filled with an open-graded aggregate coated with the asphalt binder material (Purvis, 2003). In other words, the APJ is heated to the same temperature as the asphalt binder material placed over the backer rod. A vibrating plate compactor is employed to consolidate the APJ material to fill all air voids. An additive is added to the top surface of the APJ to increase traction.

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 not vulnerable to snow plow damages.

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).

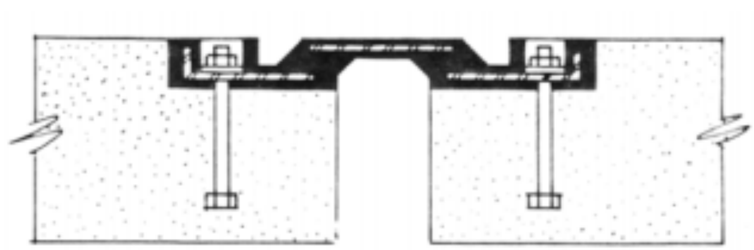


Figure 11: A Typical Cushion Joint (Purvis, 2003)

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.

Chapter 3

METHODS

3.1 Costing

To determine the total costs associated with various joint replacement actions, the owner, user, and the environment costs were determined, as depicted in Figure 1. The factors considered in the calculations can be utilized to characterize costs of past actions and to simulate future choices.

The number of workers laboring on a specific task varies throughout the day as does the amount of time spent by crew members working efficiently versus idling. 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. Idling machines have different fuel consumption and emission rates. The number of workers using a certain machine for several tasks at the same time also affects fuel consumption and emission rates. Costs are then simulated through daily material usage and emission rates collected from in field observations. The costing equations account for the efficiency and number of workers working on a task.

For most of the costing parameters, each equation will consider costs of construction activities at the task, stage, and phase levels. In the following equations, i represents the duration or time taken to complete a specific task. Being that there were few tasks that were completed with one team of unchanging personnel, j represents a segment in time when the workers laboring to complete a task was uninterrupted; Uninterrupted or continuous work means that the number of personnel working on the task was unchanging as was the manner that the task was being worked on.

The owner costs is the cost incurred to the owner through wages, fuel, and materials. Owner costs were determined by the duration, material consumption, and worker labor hours for each tool used in every segment of uninterrupted work *i*, joint rehabilitation task *j*, stage *k*, and phase *n*. Idle time of workers and tools was also considered as a cost in contrast to efficient work time. 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 through lane closures and detours. The cost to the environment was determined by the amount of EPA criteria pollutants emissions (by weight) from tools used for joint rehabilitation and increased vehicle emissions due to the presence of a work zone. These emission weights were multiplied by cost factors to calculate a total environmental cost.

3.1.1 Owner Costs

The costs incurred to the owner will be based on the wages paid 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 be owned free and clear by the contractor and will not be included in the overall owner costs. All owner costs considered are those that occurred during in-field operations.

Wages

In calculating the costs incurred to the owner, through wages, the number of workers laboring at a certain task must be accounted for over the entirety of that task's duration. The efficiency of the workers involved in a certain task can vary for a number of reasons including the fluctuating number of workers. The time work is done efficiently, i.e. with 100% work rate efficiency, or the efficient work duration is compared with the actual time to complete the task. These values are used to calculate a work efficiency rate that best reflects normal working conditions and can then be used for simulation purposes.

After the total wages for the completion of all tasks are determined, the total cost incurred through wages to complete a stage, and subsequently, a 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 workers 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.

Fuel Usage

The costs incurred through fuel usages depend on the type of machine that is being used for a specific task, and the continuous duration at which the machine is being used for a task. The fuel-type, rate of fuel consumption, and durations of continuous operating time (i.e. whether the machine is idling, or number of workers using the machine simultaneously) were factors considered in the following equations.

Material Usage

For simulation purposes the rates at which certain materials, or supplies, are used for different tasks and structural components are needed. Fuel is considered separately. Due to the wide variety of materials used in the field and the different ways at which they are applied, the dependent variable for how the rates of use are calculated can vary. For example, the rate of water use for curing of concrete was determined per hour while the rate of methacrylate usage was determined per linear foot due to the fact that. The volume of some of some of the materials were observed to be consumed in a time dependent while others could be observed to be consumed in a distance or square area dependent fashion.

Equation 3-1

$$Owner\ cost\ (OC) = (\text{Cost of}\ Wages + Cost\ of\ Materials) + Cost\ of\ Fuels$$

Equation 3-2

$$OC = \sum_{n}\left\{\sum_{k}\left\{\sum_{j}\left\{\sum_{i}(PC_L d_w + C_M U_M) + \sum_{\Upsilon} \mathrm{C}_F\left(G_{\mathrm{U}}\sum_{i}\sum_{\mu}(A_{\mathrm{G}} d_w) + G_{Id}\left(H_{\mathrm{w}} - \sum_{i}\sum_{\mu} d_{\mathrm{w}}\right)\right)\right\}\right\}\right\}$$

$n = project\ phase$

$k = project\ stage$

$j\ = project\ task$

$i = segment\ of\ uninterrupted\ work$

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

$P\ = constant\ number\ of\ workers\ on\ a\ specific\ work\ segment\ i$

$d_w = duration\ of\ effective\ labor\ by\ unchanging\ workforce\ during\ work\ segment\ i$

$U_M = use\ of\ material\ type\ M\ in\ units$

$C_M = cost\ per\ unit\ of\ material\ type\ M$

$\mu = a\ specific\ motor\ driven\ tool$

$\Upsilon = power\ generator\ for\ a\ specific\ motor\ driven\ tool, \mu$

$C_F = cost\ of\ fuel\ per\ unit\ by\ type\ of\ power\ generator\ \Upsilon$

$A_G = allocation\ constant\ for\ fuel\ use\ by\ multiple\ tools\ \mu\ using\ generator\ \Upsilon$

$G_{Id} = idling\ emission\ rate\ of\ power\ generators, \Upsilon$

$G_U = in\ use\ fuel\ use\ rate\ associated\ with\ power\ generator\ Y$

$H_w = Total\ work\ hours\ where\ the\ generator\ was\ on\ (idling\ or\ in\ use)\ by\ day$

3.1.2 User Costs

Work-Zone Road User Costs (WZ RUC) are those that are incurred to drivers and passengers due to the presence of a work zone. The WZ RUC will represent the costs incurred to society during in field construction phases, where society, in the scope of this research, is considered drivers and passengers affected by the work zone. Two quantities that, due to the work zone, impact users during construction are the time lost to drivers and the depreciation of the drivers' 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. The vehicle operating costs consider the expected fuel consumption and degradation of the vehicle through use. Vehicle operating costs are dependent on the speed and duration of vehicle travel as well as the vehicle type. Additional driving time or the time lost to all drivers is therefore the sum of the passenger delay time on the structure and increase in travel time while navigating the detours. Travel delay time is measured for all automobiles and freight trucks throughout all tasks, stages, and phases of the reconstruction process (Mallela & Sadavisam, 2011).

Congestion from increased traffic due to detouring vehicles are not considered in this 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. Due to hourly changes in traffic volumes, the travel delay time and vehicle operating costs are determined on an hourly basis.

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 drivers 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).

Vehicle Delay Time

In order to calculate the TDT and DDT, 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 vehicular delay on the structure during each weekday and weekend 24-hour period during a particular month and project phase, the duration to traverse the structure during normal conditions was found by dividing the bridge length (in miles) by the normal travel speed (in miles per hour). 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.

In the case of partial lane closure in one direction in the work zone, the same number of vehicles were assumed to cross the bridge as under normal conditions. When there was a complete closure of all lanes in one direction of travel during the work zone all vehicles were then assumed to take the detour. During different phases n of the project partial or total lane closure in a direction of travel might occur. Equations 3 and 4 describe the vehicle delay time, the difference in time between when a vehicle traverses the work zone (Equation 3-3) or over every detour link *z* (Equation 3-4) as compared to the time it takes to traverse the structure under normal traffic conditions. Equations 5 and 6 describe the road user costs in terms of traveler delays and increased vehicle operation due to the presence of a work zone.

Equation 3-3

$$VD_{WZ} = \frac{L_{WZ}}{S_{WZ}} - \frac{L_{ST}}{S_{ST}}$$

Equation 3-4

$$VD_{DT} = \sum_{z} \left(\frac{L_{DT}}{S_{DT}}\right) - \frac{L_{ST}}{S_{ST}}$$

$VD = Vehicle\ delay\ (Vehicle - hours\ )$

$S = Speed\ (miles\ per\ hour)$

$WZ = Workzone$

$ST = Structure$

$DT = Detour$

$Rt = Route, either\ workzone\ or\ detour$

$L = length\ (miles)$

$z = Specific\ component\ of\ detour\ i.e.detour\ link$

Traveler Delay Cost in Work-Zones and Detours

Total traveler delay cost is the cost of time delays incurred to vehicles traversing the structure at a reduced speed than normal due to the presence of a work zone summed with the costs of time delays to vehicles navigating the detours during all phases of the project until completion. After the vehicular travel delay is determined, the values must be scaled by the number of drivers 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 drivers and passengers of each vehicle type is determined. By summing the delayed time incurred to drivers 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 drivers and passengers is determined. 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 passenger delay costs on the structure and detours, the cost of time depends on whether the passengers are traveling via automobile or truck and for personal or commercial travel purposes. The phase identifier will determine the direction of travel due to the fact that each phase is assumed to have only one direction of travel with the other direction closed off due to the work involved.

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 depend on speed, the vehicle-type, and distance traveled; different speeds have different vehicle operating costs. 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 to determine the total operating costs associated with the durations, work zone lane closures, and detour lengths of each phase.

Vehicle Operating Cost in Work Zone and Detours

The lengths and speed of each phase's detour and the related detour links differ and thus the vehicle operating costs differ. The detour lengths will be expressed as the sum of every detour link associated with a particular phase. 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, hour, and the type of day (weekend or weekday), over all phases of construction, the total operating costs of all vehicles traversing structure is determined (Equation 3-9). Note that for vehicles traversing the detour, 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. 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.

Total Road User Cost

Equations 3-5 and 3-6 describe the road user cost. Increased vehicle operating costs are only considered for the vehicle traffic that uses the detour since the total distance travelled is greater on the detour.

Equation 3-5

Road user cost (RUC) = Traveler Delay Cost + Increased Vehicle Operating Costs

Equation 3-6

$$RUC =$$

$$\sum_{n}\left\{\sum_{k}\left\{\sum_{j}\left\{\sum_{h}\left\{\sum_{Dy}\left\{\sum_{V}\left\{\sum_{Rt}\left\{\sum_{\Delta} C_{V}AVO_{V}AHT_{V}VD_{Rt}\right\}\right\} + C_{O}AHT_{V}\left(\sum_{z} L_{DT} - L_{ST}\right)\right\}\right\}\right\}\right\}\right\}$$

$h = hour\ of\ the\ day$

$Dy = Day, either\ weekend\ or\ weekday$

$V = Vehicle\ type, either\ automobile\ or\ truck$

$Rt = route\ travelled, either\ detour\ (DT)\ or\ workzone\ (WZ)$

$\Delta = Direction\ of\ vehicles\ travelling$

$C_V = Cost\ per\ hour\ for\ personal\ (automobile)\ or\ commercial\ (truck)\ time$

$C_O = Cost\ of\ operating\ vehicle$

$AVO_V = Average\ vehicle\ occupancy\ by\ vehicle\ type\ V$

$AHT_V = Average\ hourly\ traffic\ by\ vehicle\ type\ V$

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 emitted pollutants can then be estimated throughout each task, stage, phase, and when idling or in use. Based on the weight of each type of 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 in field activities have on the environment. After the emission rates are determined, they will be converted into total weights 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.

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 a generator or combusted fuels directly. 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, air blasters, sandblasters, and silicone applicators that in turn powers those tools. There were only three motor driven tools used that were not connected to an external power source, the skid steer loader, the 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 air emissions factors for engines used both for on-road and non-road applications (Environmental Protection Agency, 2015). The emission factors for equipment, e.g. the air compressor, are determined by the emission type, equipment type, horse-power, fuel type, location, date, and time of day. The equipment is organized into 12 industry subdivisions such as agricultural, commercial, construction, industrial, and recreational. The emission rates outputted are for EPA criteria pollutants - 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 corresponding emission rate constants are shown in Table 12.

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 grams per horsepower-hour (g/hp-hr); by logging the durations at which the equipment is being used and its horse-power, the volume of pollutants can be determined.

A power generator or the air compressor powered multiple tools at the same time. When multiple tools were powered at the same time, the emissions from the generator were divided by the number of tools. For the air compressor, allocation was based on recorded tools based on the rotation per minute (rpm) values of the tool motors in use; greater rpm values were allocated proportionally a greater amount of emissions. When rpm values were not available the emissions from the power generator were simply divided by the total number of tools in operation at that time. If the tool was not connected to an external power generator, the allocation constant, *A,* simply becomes 1 and has no effect on the emission cost calculation for a specific task, stage, or phase. Idling of the power generators are considered separately since idling has different emission rates than use. The total weight 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 (Equations 3-7 and 3-8).

Equation 3-7

Cost of Tool Emissions (E_T)= Emissions cost from Tool Use + Emissions cost from Tool Idling

Equation 3-8

$$E_T = \sum_{x}\left\{\sum_{n}\left\{\sum_{k}\left\{\sum_{j}\left\{\sum_{\Upsilon} C_X\left(R_U\sum_{i}\sum_{\mu}(A_R d_w) + R_{Id}\left(H_w - \sum_{i}\sum_{\mu} d_w\right)\right)\right\}\right\}\right\}\right\}$$

$x = Specific\ emission\ type\ signifier$

$C_X = Cost\ of\ emission\ type\ x\ in\ dollars\ per\ gram$

R_U
$= In\ use\ emission\ rate\ of\ specific\ emission\ type, x, associated\ with\ power\ generator, \Upsilon$

R_{Id}
$= Idling\ emission\ rate\ of\ power\ generators, \Upsilon, for\ specific\ emitted\ pollutants, x$

$A_R = Allocation\ constant, assigns\ percentage\ value\ of\ emission\ rate\ between\ tools$

Vehicular Emissions

There are two types of models, static and dynamic, that can be used to determine emission factors from vehicles (Mallela & Sadavisam, 2011). Static 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 used for future planning purposes based on average speeds; "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). These same factors were also not considered when determining the road user delay costs.

Dynamic models necessitate precise traffic collection data at the exact location of the work zone to capture the vehicles' acceleration, deceleration, idling, and cruising due to the work zone and traffic signals. The same as 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, 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, except California (Mallela & Sadavisam, 2011). California has its own model, the Emission Factor (EMFAC) model (see Table 7), which was developed by the California Environmental Protection Air Resource Board (CARB) to estimate mobile vehicle emissions ("Mobile Source Emission Inventory -- Categories," n.d.). The average hourly traffic (AHT) of both trucks and automobiles traversing the work zone and the detours, for each phase, must be considered to determine the volume of each pollutant emitted by the vehicles. The total pollutants emitted due to vehicular transport is the sum of the increased pollution of vehicles traversing the work zone and the detours. By multiplying the AHT determined for the road user costs, 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 (Equation 3-9).

Equation 3-9

$$E_V =$$

$$\sum_{x}\left\{\sum_{n}\left\{\sum_{k}\left\{\sum_{j}\left\{\sum_{h}\left\{\sum_{Dy}\left\{\sum_{V}\left\{\sum_{\Delta} C_X AHT_V \left(R_{V,WZ}L_{WZ} - R_{V,ST}L_{ST} + R_{V,DT}\sum_{z} L_{DT} - R_{V,ST}L_{ST}\right)\right\}\right\}\right\}\right\}\right\}\right\}\right\}$$

$$R_V = emission\ rate\ of\ specific\ emission\ type, x, by\ vehicle\ type\ and\ speed^*$$

*Note: speed depends upon the route taken, workzone WZ, detour DT, or structure ST under normal traffic conditions

Costing of Emissions

There is no general consensus on how to monetize environmental impacts due to emitted pollutants. One way to monetize the environmental impacts of emissions is to determine the general health impact incurred to a specific population; Exposure of a specific population to a certain dose of emissions will result in a health response, in terms of increased incidence of disease and adverse health conditions, which will incur health related costs (Mallela & Sadavisam, 2011). In urban areas where the population is denser, the costs associated with pollution are likely to be higher than similar emission volumes expelled in a less densely populated suburban area, depending on background emission levels. Two resources suggested by the FHWA to use to monetize health impacts are estimates from The Highway Requirements System-State Version (HERS-ST) 2005 Technical Report and the California Department of Transportation (Caltrans) (Mallela & Sadavisam, 2011). The cost factors used are constant. The environmental cost scales with the emission rates. 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 (Equation 3-10).

Equation 3-10

Environmental cost (*EC*) = Tool Emissions Cost (E_T) + Additional Vehicle Emissions Cost (E_V)

Life Cycle Inventory

A joint replacement operation on a structure was shadowed to gather all necessary data in order to construct a life cycle inventory. The duration, material consumption, and emission rates associated with the demolition, cleaning and construction processes were gathered for simulation purposes. Through all stages of the operation, the duration and number of workers laboring to complete a specific task were recorded as well as the idle 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 by a relevant unit of use, e.g. square foot of concrete demolition. Recording task information in this way allowed for simulation of the owner, user and environmental costs associated with different joint replacements.

3.1.4 Case Study Location and Time

The bridge used in this case study is owned by the Delaware Department of Transportation (DelDOT); DelDOT is responsible for the maintenance of the structure. The Edgemoor Road toll-free bridge is inspected every 2 years and was last inspected February 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.

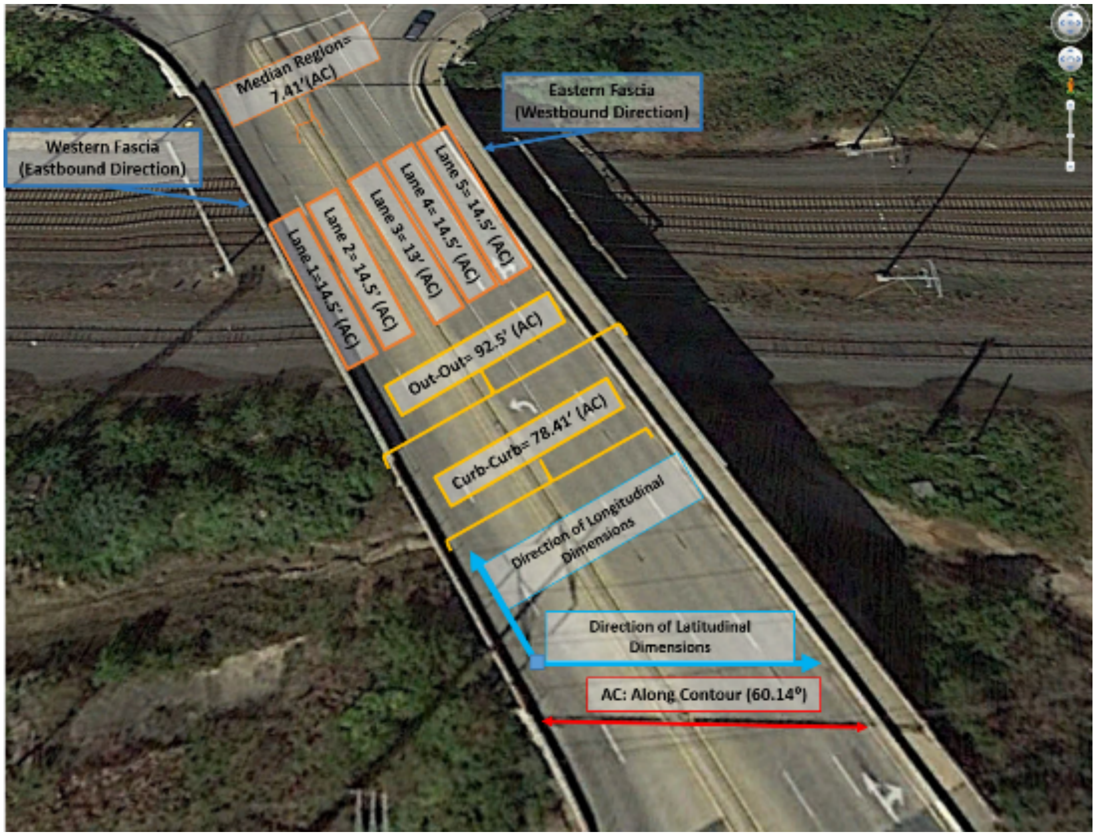


Figure 12: Edgemoor Road over Amtrak and Norfolk Southern Bridge; Latitudinal Dimensions, Pre-Construction Image

As determined by the FHWA NBI, and verified through in field inspection, the the superstructure is 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 has a 30° skew, and does not have any flare and the two abutment joints of the bridge are contoured by 60° 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 in-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° contour on the bridge. For example, the width of the roadway on the southern edge of the bridge upon which the southern abutment joint is 68 feet, but the actual length of the joint is measured along the contour at 78.42 feet. The measurement along the contour relate to the actual length of the joint, whereas the normal length relates to the characteristics of the roadway on the bridge at that same point in the structure. All dimensions recorded as lateral measurements should be assumed to be along the contour.

All dimensions recorded are relative to the southern abutment joint of the bridge (Table 14). 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.

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

3.1.5 Case-Study Overview

From the in-field observations the replacement of the Southern abutment of Edgemoor road can be categorized into the three stages - 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. Note that work was neither done on weekends nor on rainy days. Work hours usually ranged between 7:30 AM to 3:30 PM.

Table 15: Total Duration of the Demolition and Construction Stages

Stage	Start Date	End Date	Total Duration (days)
Demolition	7/30/2015	8/6/2015	7
Construction	8/6/2015	8/25/2015	19

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 idling time affects these costs.

Table 16: Total Worker-hours in 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%

This research only covers the southern joint replacement of the Edgemoor Road bridge. The following other maintenance activities occurred on the northern end of the bridge during Phase 1 on the closed eastbound direction traffic lanes:

- 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, and
- removal and replacement of the epoxy and backer rods of the parapet and the riding surface between the backwall and approach.

Phase 1 of the southern expansion joint replacement consisted of the following activities in order of completion. Simultaneous demolitions of the deck and backwall concrete headers, forming the dam blockout to make a full depth removal, and removal of the traffic parapet and partial removal of the wingwall supporting said parapets along the backwall and deck headers.

The blockout is the rectangular portion of the riding surface that surrounds the joints forming the headers. During the case study, the area where rehabilitation and replacement was to take place around the joint (including the blockout) was first outlined with a line cut parallel to the entire length of the joint with a saw and then the material within was demolished. 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 are subject to either partial depth or full depth removal.

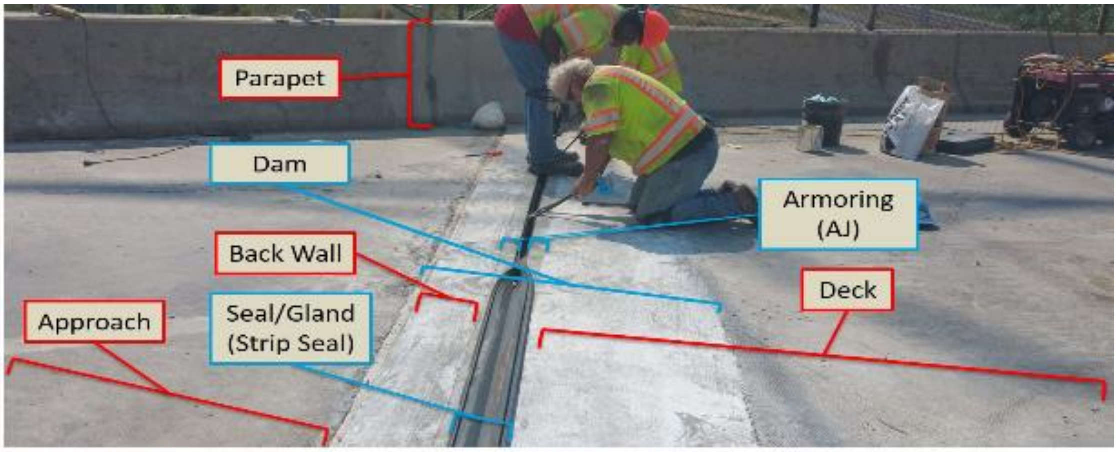


Figure 13: Components Associated with the Replacement of the Southern Abutment Joint Post-Construction

Figure 13 depicts the main components of the bridge subject to demolition and construction. Figure 14 depicts the wingwall underneath the demolished parapet that was next to be demolished. All tasks associated with the demolition, construction, and cleaning stages are described in Appendices A, B, and C, respectively. In Appendices A, B, and C, step-by-step procedures, the durations to complete said tasks, the rates of completion and material usages, and commentary are provided for all tasks.


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

3.1.6 Additional Impacts Observed

One concern that came up during the case study 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. Workers are directly exposure to maintenance and repair related emissions either from operations or traffic delays. Estimating these types of impacts was beyond the scope of this research. However, it would be advisable that construction equipment be designed to impose less physical stress on workers and that construction operations work to minimize pollutant exposure to workers. Had these impacts been incorporated as costs, the environmental costs (and thus human health costs) evaluated in this case study would have increased. 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.

Chapter 4

ANALYSIS

4.1 Case Study Costs

Utilizing the methods chapter, the analysis chapter provides 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 to the owner, society, and environment of the case-study joint replacement operation were calculated. The owner costs include all costs incurred to the contractor for replacing the expansion joint headers and sealant. The user costs are those incurred to users of the roadway due to lost time from taking detours or reduced speeds across a structure with a work zone and from increased vehicle operating costs. The environmental costs are the health impacts related to emissions from equipment and tools used on-site and due to increased emissions from vehicle operating changes due to detours and the work zone. This section will expand upon the methods section by considering data collected and analyzed and the costing results.

4.2 Owner Costs

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. The time each crew member worked on tasks and how much of that time was spent efficiently and idling was recorded on a daily basis. 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. For example, if a worker labored on Edgemoor Road for three

Table 17: Wages and hours by labor type ("Prevailing Wages for Highway Construction," 2014)

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%

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. The total wages paid by the owner depend on the hourly rate received by the workers. There were five types of workers with different hourly wages working in the field during the operation; a 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. 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 is not calculated in the following owner costs. Appendix D.1 includes the following data;

- 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, and
- Total wage costs incurred per worker-type, idling and the efficiency of worker-types based on monetary values.

The total cost of wages incurred to the owner was $19,645 as shown in in Table 17. 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; a foreman's responsibilities in oversight and supervision were evidenced in how the workers knew exactly what task to work on, how to resolve

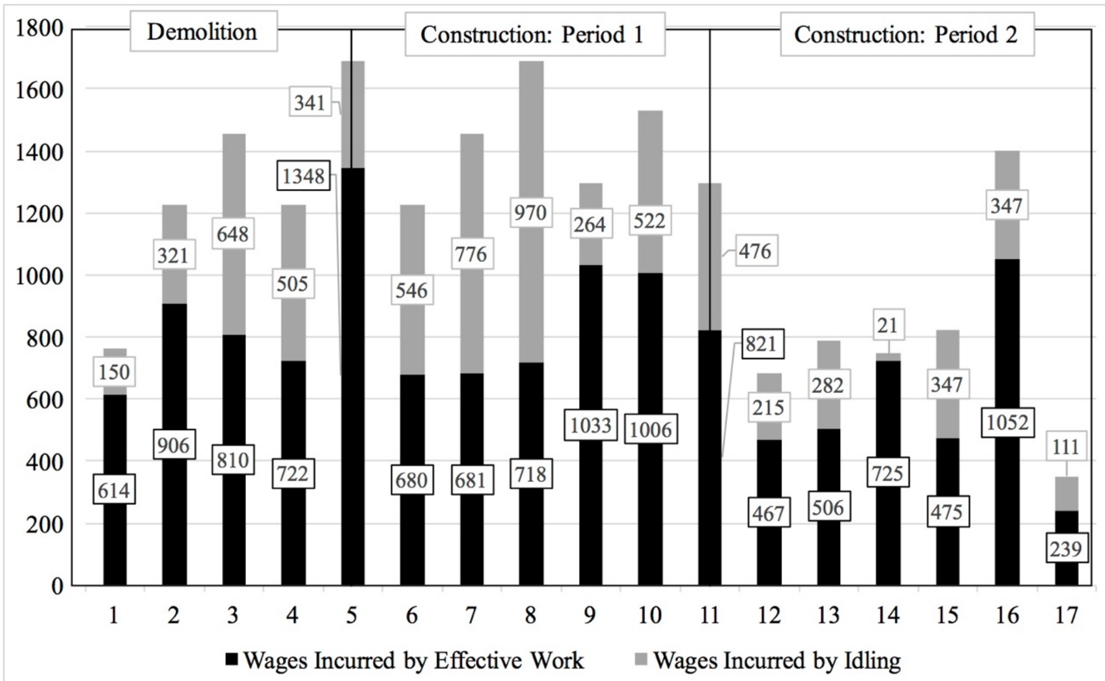


Figure 15: Wages Paid by Owner on a Daily Basis Throughout of All Stages and Periods Including Effective Work and Idling

certain issues, and how to complete a task. Figure 15 shows the fluctuation in wages paid, or owner costs, on a daily basis.

On a daily basis, the wages fluctuated based by the hours worked and the number of workers in the field. Thus, the cost of $19,645 represents the cost paid by the contactor to its workers; since the data was collected for each worker and each individual task, the efficiency of the worker can 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 the following two reasons; concrete saw cutting of the headers occurred before the crew arrived on site and the pouring of the concrete occurred concurrently with the shoveling, and vibrating of said concrete.

The effective number 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 in 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

4.2.1 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 are listed in Table 19.

Table 19: In-Field Power Sources' Fuel Consumption

Power Source	Brand	Model	Fuel-Type	Operating Rate (gallons/hr)	Idling Rate (gallons/hr)
Electric Power Generator	Honda	EB 5000 X	Gasoline	0.77	0.55
Portable Air Compressor	Airman	PDS 185S	Diesel	1.23-2.31	0.8
Skid Steer Loader	Bobcat	S650	Diesel	1.5-2.4	0.4
Power Driven Welder	Miller	Big Blue 400 Pro	Diesel	0.65	Not Applicable

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 were determined separately. For the electric power generator, a fuel gauge was visible and data was logged each day. The data logs were comparable 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 determined by logging the start and stop times throughout each day. The amount of fuel consumed was calculated when the electric generator, with a tank size of 6.2 gallons, was operating and idling (Table 20).

Table 20: Electric Generator's Effective and Idling Operation and Fuel Consumption

	Effective Operation	Idle	Total
Time (hrs)	33.93	20.22	54.15
Percent Time	62.66%	37.34%	100.0%
Fuel Consumption (Gal)	26.13	11.12	37.25
Fuel Use %	11.63 % for Cleaning/ 58.51% for Construction	29.85%	100.0%

A fuel gauge was also available on the air compressor (an Airman PDS 185S-6E1); however, the machinery had mechanical issues making the readings unreliable. A log of the motor's frequency of rotation, in rotations per minute (rpm) for all tasks was taken. For determining the environmental impacts, the rpms were allocated to each of the seven tasks the airman was used for in Table 21.

Table 21: Rpms Logged from the Air Compressor for Each of its 7 Allocations

Arrangement	Reading	Units
1. Idling	1200	Rpm
2. One Breaker	1680	Rpm
3. Two Breakers	2102	Rpm
4. Three Breakers	2550	Rpm
5. Airblasting	2813	Rpm
6. Sandblasting	2900	Rpm
7. Applying Silicone (AT1200S)	1275	Rpm

To relate the rpms to the fuel consumption technical data, guidance and assumptions were made from speaking with the distributor and owner of the air compressor MMD Equipment. The specifications for the Airman PDS 185S-6E1, provides a relationship for between the load experienced by the generator to the rpms produced ("Airman PDS185S-6E1 Air Compressor | MMD Equipment," n.d.). Three load to fuel consumption relationships were provided: 0% Load (idling) - 0.8 gallons per hour; 70% Load: 1.7 gallons per hour; and 100% Load: 2.4 gallons per hour.

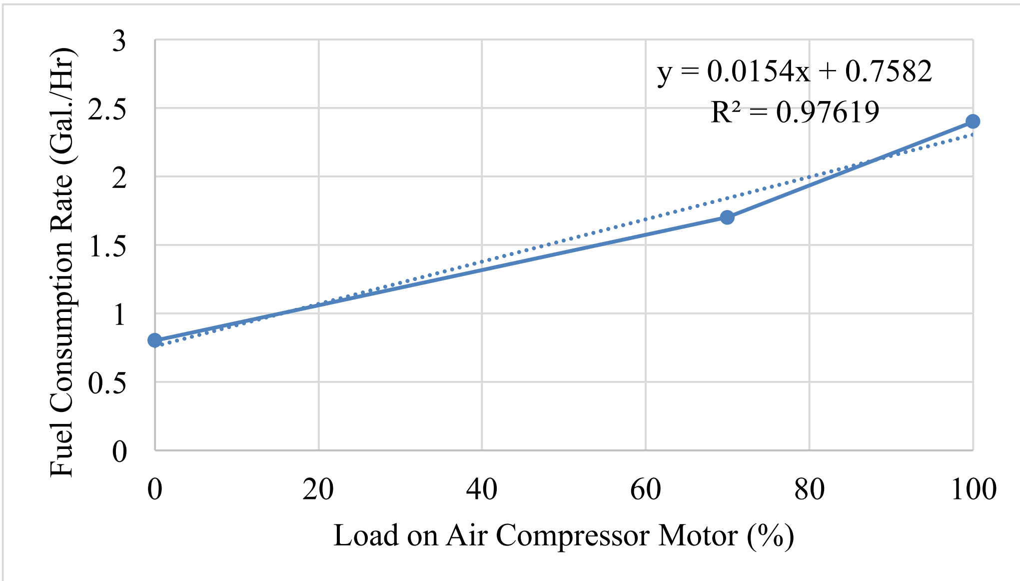


Figure 16: Loading on Air Compressor in percentage terms compared with the Fuel Consumption Rate (gallons per hour), the linear regression curve is represented by the dotted line.

A relationship between low idling and high idling, was also given in the specifications as a low idle was up to 1350 rpms, where as a high idle was at least 3000 rpms. The relationship between the rpms and percentage load is provided in Figure 16. A linear least-squares regression was performed to generate an equation to interpolate between known data points. The R^2 value is of sufficient value to treat the relationship as 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	0.80
2. One Breaker	1680	1.23
3. Two Breakers	2102	1.60
4. Three Breakers	2550	2.00
5. Airblasting	2813	2.23
6. Sandblasting	2900	2.31
7. Applying epoxy (AT1200S)	1275	0.87

Table 23 provides the total operating times (both effective and idling) for the entire case study and the resulting fuel consumptions. The last four rows in Table 23 provide 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 (hr)	23.50
Total Idling Time (hr)	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 are tabulated in Appendix D.2.

Like the electric generator, the air compressor was left on for an extended number of hours per day. Activities associated with the skidder spanned the demolition, construction, and cleaning stages and included breaking, driving, lifting, and idling. For such activities, fuel consumption rates were not available from equipment manufacturer's specifications. 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 Tasks (Stages)

Action/Stage	Fuel Consumption Rate (Gal/hr)
Idling	0.4
Breaking/Demo.	2.4
Driving/Cg.	1.5
Lifting/Const.	2.0

Table 25 provides the total operating times (both effective and idling) for the entire case study and the resulting fuel consumptions. Table 25 shows that due to a low idling fuel consumption, the skidder had a relatively small use of fuel for idling compared to the time the skidder spent idle. The amount of time spent efficiently working (per allocated task) and idling, on a daily basis, and the subsequent fuel consumptions are tabulated in Appendix D.2.

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

Total Operating Time (hr)	14.32
Total Effective Operating Time (hr)	10.08
Total Idling Time (hr)	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 for Demo.	50.91
% of Fuel for Cg.	35.72
% of Fuel for Const.	5.36
% of Fuel for Idling.	8.01

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, drawing a continuous 150 Amperes. The fuel consumption rate was taken from the manufacturer's specifications at 0.65 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 are tabulated in Appendix D.2. Table 26 provides the durations and fuel consumptions of all of the power sources used in the field by 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 (hr)	%	Duration (hr)	%	Duration (Worker-hr)	%	Duration (hr)	%	Duration (Worker-hr)	%
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

Fuel Consumption Costs

To determine the cost of all of the fuel used (113 gallons of diesel and gasoline), the U.S. Energy Information Administration (EIA) was referred to for the representative time period (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 Coast Cost of Gasoline per Gallon	2.47
Average East Coast Cost of Diesel per Gallon	2.71

Thus, with the durations of power source fuel usages for idling and effective work, the fuel type and usage rate of each power source, the total costs can be determined as are provided in Table 28. Total fuel cost is therefore $297 of which 21.3% 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

4.2.2 Material Costs

The materials used in the demolition stage were the gases for the torching and heat cutting tasks, which used two tanks of dissolved acetylene and compressed oxygen contained in 145 and 228 cubic foot tanks, respectively; the ratio for each of these gasses was roughly 1:1. Thus, acetylene would run out 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 are provided in Appendix D.3 with commentary.

The total costs of all materials used throughout all stages of the phase was $18,090. 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	42.34

Steel Reinforcement	$1,090	6.03
Adhesives for Steel Reinforcement	$142	0.78
Formwork Material	$426	2.36
Concrete and Related Materials	$601	3.32
Armoring System and Extrusion	$7,730	42.73
Silicone and Methacrylate	$262	1.45
Cleaning and Demolition	$179	0.99
Total Material Cost	$18,090	100%

As can be seen in Table 29, the majority of the material costs incurred to the owner were from the pre-demolition and the armoring system and extrusion material costs; together these costs accounted for 85.1% of the total material costs or $15,390. The third most expensive cost was the steel reinforcement at $1,090, 6.03% of the total material costs.

4.2.3 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	51.90
Fuel Consumption	$113	0.30
Material Consumption	$18,090	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 99.7% of the costs, or $37,754. The costs of wages and material consumption, of $19,645 and $18,090, respectively, were quite close in value. As previously shown, the idling fuel cost was 21.3% of the total fuel cost. Worker idling hours cost $6,842, or 18.1% of the total costs incurred to the owner. Although 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 totally eliminated and that it is necessary for workers to rest at times to be able to carry on doing backbreaking labor throughout the day.

4.3 Societal Costs of Case Study

The societal costs, or the delay and vehicle operating costs incurred to users, are 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 takes a detour. At the same time, two of the three lanes of the westbound direction were closed. The increase in travel time for the westbound direction was considered inconsequential and not enough to cause drivers 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 increased congestion.

4.3.1 Road-User Database

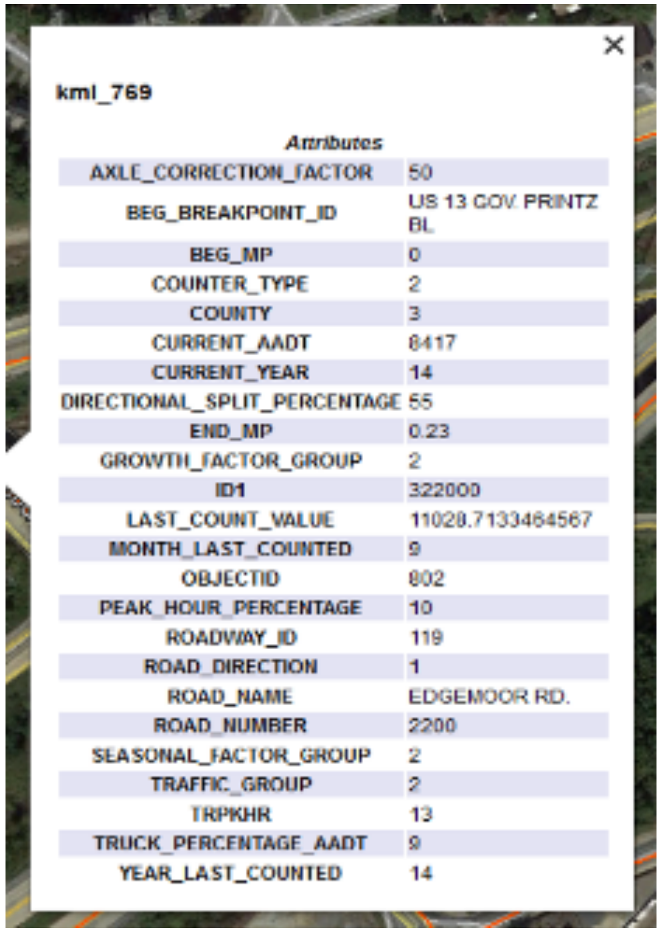
The acquisition of traffic data before, during, and after construction on the bridge is of the upmost importance in determining the societal costs. The collection of traffic data in the state of Delaware is done so in compliance with DelDOT. Specifically, DelDOT utilizes its Traffic Monitoring System (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 directions of traffic.

Traffic Pattern Groups (TPGs), attained from the Delaware Vehicle Volume Summary Book of 2014, were used to determine the number of average daily users traversing the bridge in the east and westbound direction. 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 eight TPG's that represent 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, and
- 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 fall under TPG 2.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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	11028.7133484567
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 (DelDOT, 2014b)

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 can the data calculated be considered completely accurate. Uninterrupted flow is the only considered case in this study. The vehicle operating and passenger delay costs presented throughout this report 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 number 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. The strategies and data utilized in determining the vehicular volume for the case-study are provided in Appendix E.3.

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	61394
	Total Automobiles on Structure: Weekdays	Total Automobiles on Structure: Weekdays
	8771	75037
Automobiles: Weekends	Total Automobiles on Detour: Weekends	Total Automobiles on Detour: Weekends
	0.0	28883
	Total Automobiles on Structure: Weekends	Total Automobiles on Structure: Weekends
	0.0	35301
Trucks: Weekdays	Total Trucks on Detour: Weekdays	Total Trucks on Detour: Weekdays
	710	6072
	Total Trucks on Structure Weekdays	Total Trucks on Structure Weekdays
	867	7421
Trucks: Weekends	Total Trucks on Detour: Weekends	Total Trucks on Detour: Weekends
	0.0	2857
	Total Trucks on Structure: Weekends	Total Trucks on Structure: Weekends
	0.0	3491

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 (hr)
US13	35	2.0	0.06
12th Street	25	0.9	0.04
Ramp (from 12th)	25	0.2	0.01
Totals	-	3.1	0.10

Since the effect of detouring vehicles on the bypasses are not considered in this 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 drivers traversing the structure with the presence of a work zone, however, is determined on an hourly basis. Speeds are assumed to decrease due to the work zone as shown in Table 33.

The strategies and data utilized in determining the vehicular speed on the structure before and during the work zone are 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.

Table 33: Designated Speeds on Edgemoor Road, with Work-Zone, Westbound Direction During Weekdays and Weekends (Google Maps, 2016)

Hour	Weekday Speeds (mph)	Weekend Speeds (mph)
	Westbound	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

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 drivers 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 average vehicle occupancy (AVO). Freight trucks are considered to have AVO of 1; passenger vehicles are considered to have 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 were found to be trucks, the remaining 81% were passenger vehicles. 55% of vehicles traveled 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 drivers, organized by the type of vehicle being driven as shown in Table 34. With the vehicle operating cost constants provided by DelDOT, intermediary values were analyzed and shown in Table 35 and correlated in Appendix E.5 for analysis.

Table 34: DelDOT, 2015 Value of Time ("Design Guidance Memorandum Road User Cost Analysis," 2015).

Vehicle Type	Cost ($/hr)
Auto	19.8
Light Trucks	19.6
Heavy Trucks	29.1

Table 35: DelDOT, 2015 Vehicle Operating Cost ("Design Guidance Memorandum Road User Cost Analysis," 2015).

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

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	$3,383	$6,209
	On-Detour	$0	$0	$0
Passenger Delay Costs ($)	On-Structure	$6,043	$6,311	$12,355
	On-Detour	$0	$0	$0
Total Road User Costs ($)			$18,564	

The total road user costs can now be determined with the following by first determining the total road user cost incurred to drivers and passengers during normal conditions 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,

- 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

As seen in Table 36, road users in the eastbound direction incur less cost than those in the westbound direction and are 45.5% versus 54.5% of the total vehicle operating cost without the work zone. 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 48.9% versus 51.1% of the total passenger delay costs. 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. This value is subtracted from the costs incurred due to the work zone to avoid double counting vehicle operating and passenger delay costs. The total vehicle operating and passenger delay costs were 33.5% and 66.6% 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	$3,806	$3,806
	On-Detour	$174,966	$0	$174,966
Passenger Delay Costs ($)	On-Structure	$0	$12,926	$12,926
	On-Detour	$343,349	$0	$343,349
Total Road User Costs ($)			$535,047	

As seen in 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 as the only direction that was considered to take the detour was the eastbound direction. 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 had to take. Similar to the proportions calculated for the normal traffic conditions within the time range of the case study, the vehicle operating and passenger delay costs were 33.4% and 66.6% of the total road user costs incurred due to the work zone of $535,047.

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 they do 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.

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	$423	$423
	On-Detour	$172,140	$0	$172,14
Passenger Delay Costs ($)	On-Structure	$0	$6,614	$6,614
	On-Detour	$337,306	$0	$337,306
Total Road User Costs ($)			$516,483	

The net value of the total road user costs is $528,552. Similar to the road user costs under normal and work zone conditions, vehicle operating costs and passenger delay costs were consisted of 33.4% and 66.6% of the total road user cost of $516,483. 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 98.6% 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 Case Study Environmental Costs

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 amounts and costs of emissions produced by each power source used in the field. This section will also provide the increase in and costs of emissions from vehicles traversing the work zone and detours.

4.4.1 In-Field Power Sources' Environmental Impact

Multiplying how long, the duration of, each power source was used by pollutant emission rates calculates the total amount of pollutants emitted. Emission rates are different for equipment that is idling or operating fully. The pollutants considered are EPA criteria pollutants as shown in Table 39. Durations spent working and idling were converted to emitted pollutants by utilizing EPA MOVES software emission factors. In MOVES, the emission factors 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 were 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 a similarly urban location near the coast. A costing factor was given for PM10 by MOVES but not given for PM2.5; thus, the HERS-ST EEA tool was used to determine the proportional value 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, PM2.5 utilized the same costing factor as PM10. The amount of emitted pollutants for each power source was calculated by multiplying the emission factors by how long the power source was used both effectively and when idling. The total emissions for the electric generator are shown in Table 40.

Table 39: Emitted Pollutants Considered for Costing Purposes

Emitted Pollutants
Atmospheric CO_2
Carbon Monoxide (CO)
Fine Particulate Matter (PM 2.5)
Oxides of Nitrogen (NO_x)
Road Dust (PM 10)
Sulfur Dioxide(SO_2)
Volatile Organic Compounds (VOC)

Table 40: Total Emissions for Each Power Source (tons)

Emitted Pollutants	Emitted Pollutants of Power Sources (tons)				Total Emissions per Pollutant (tons)
	Electric Generator	Air Compressor	Skidder	Power Driven Welder	
Atmospheric CO_2	0.551	1.09	0.630	4.39E-02	2.31
Carbon Monoxide (CO)	0.145	2.01E-03	5.40E-03	3.86E-04	0.153
Fine Particulate Matter (PM 2.5)	5.46E-05	3.25E-04	7.92E-04	5.19E-05	1.22E-03
Oxides of Nitrogen (NO_x)	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(SO_2)	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

Table 41: Costing Factors Utilized with Mass of Pollutants Emitted

Emitted Pollutant	$/ton

Atmospheric CO2	$23
Carbon Monoxide (CO)	$75
Fine Particulate Matter (PM 2.5)	$139,900
Oxides of Nitrogen (NOx)	$12,900
Road Dust (PM 10)	$139,900
Sulfur Dioxide(SO2)	$69,800
Volatile Organic Compounds (VOC)	$1,210

The costing factors of emission cost per ton from the MOVES software (Table 41) was used to calculate the cost of the total weights of pollutants emitted. 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 in dollars per ton.

Table 42 provides the total costs due to effective and idling processes per power source and the total environmental cost. Thus, the total environmental cost of the power sources was $600. Idling of power sources resulted in 32.3%, or $194, of the total cost.

Table 42: Total Environmental Costs Due to Power Sources

Emitted Pollutants	Emitted Pollutant Costs ($)		Total Cost ($)
	Idling	Effective	
Electric Generator	$21.7	$36.5	$58.2
Air Compressor	$81.6	$133.6	$215.2
Skid Steer Loader	$90.6	$215.7	$306.2
Engine Driven Welder	$0.00	$20.6	$20.6
Total Idling Cost		$194	
Total Effective Cost		$406	
Total Cost		$600	

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 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	$0.19	$249
Oxides of Nitrogen (NOx)	$10,637	$45.6	$10,683
Road Dust (PM 10)	$3,230	$29.2	$3,260
Oxides of Sodium (Sox)	$330	$4.61	$335
Volatile Organic Compounds (VOC)	$384	$3.12	$386
Total Costs	$14,830	$82.7	$14,913

Thus the total environmental impact of the vehicles traversing the structure (in the westbound direction) and those traversing the detours (eastbound direction) equates to $14,913. The westbound direction only provided $82.7 of the total environmental impact due to speed slowdowns with the work zone. The rest of the $14,830 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 at slower speeds.

Thus, the total environmental cost, including the on-site power sources and extra vehicle travel due to the work zone, was $15,513, of which 3.87% of the total cost was due to the on-site power sources, and 96.1% 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 Category and Component

Costing Category	Costing Components	Components' Costs	Total Cost of Category	Percentage of Total
Owner Costs (A)	Wage Costs	$19,645	$38,033	6.67%
	Fuel Costs	$297		
	Material Costs	$18,090		
Road User Costs (B)	Vehicle Operating Cost	$172,563	$516,483	90.6%
	Road User Cost	$343,920		
Environmental Costs (C)	On-Site Power Source Env. Cost	$600	$15,513	2.72%
	Vehicular Env. Cost	$14,913		
Total Cost		$570,028		

Thus, the total cost incurred to the owner (A), society (road users) (B) and the environment (C) totals $570,028; Of the total 6.67% of the cost is due to the owner costs, 90.6% is due to the road user costs, and 2.72% is due to the environmental costs. Note that 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 deceleration and acceleration of the vehicles all contribute to the total road user and environmental costs but were neglected in this study.

That said, environmental and owner costs considered only a limited number of items. Environmental impacts due to emissions to water and soil were ignored as was noise. Environmental damage categories such as toxicity were ignored as well. This was only a barebones framework for including environmental impact in a very simplified life cycle assessment format – a full life cycle assessment would include evaluation of the extent and significance of all impacts to air, water, soil, people and other species. Also there is wide disagreement about whether the extent of environmental damages can even be accurately represented by costs especially future costs: it should be presumed that costs associated with environmental damages are uncertain at best (Martinez-Alier, Munda, and O'Neill, 1998).

Costs incurred by idling of either workers and/or equipment in terms of wages, fuel, and the environmental impact summed to $7,099. Of this total 96.4% went towards wages, 0.89% towards fuel and 2.73% towards environmental impact. The total costs incurred from 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.

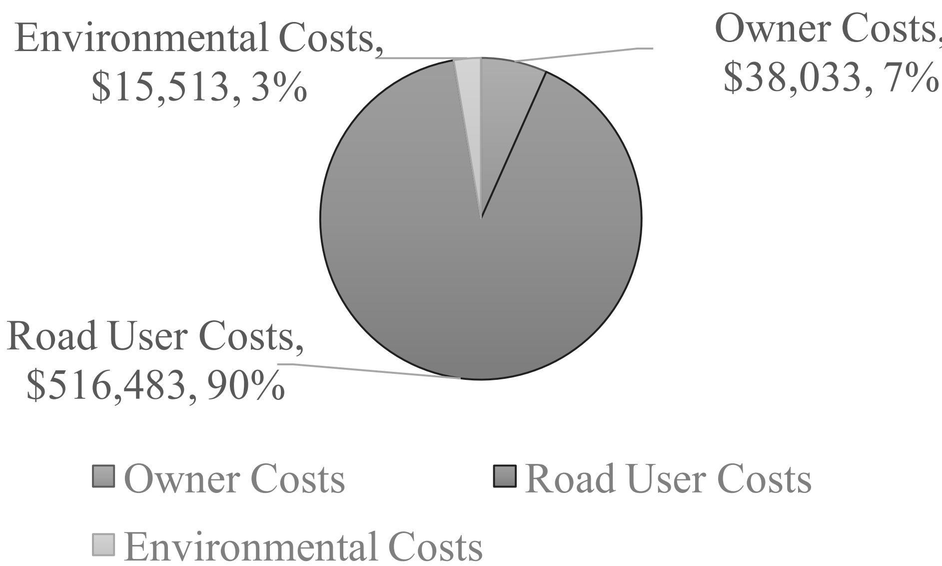


Figure 18: Total Costs Depiction per Costing Category

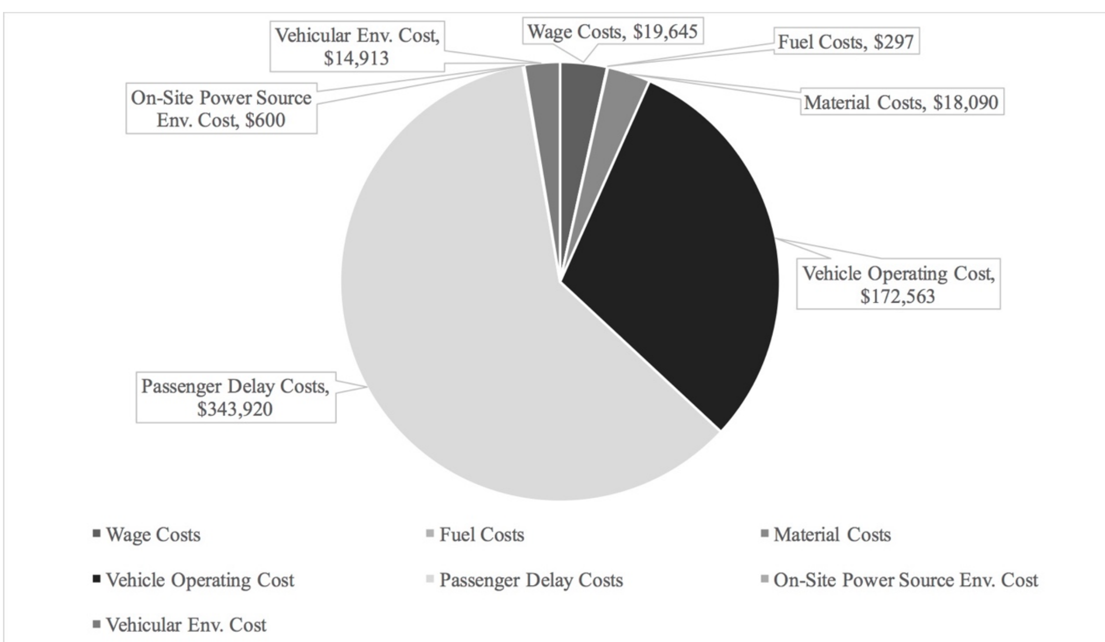


Figure 19: Breakdown of Costing Categories into its Components

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 joint systems. Utilizing the durations, rates, and costs associated with the full depth replacement of the headers and sealants of the Edgemoor Road bridge, this section simulates and optimizes the durations and costs associated with the following tasks.

- Partial depth removal of the backwall, deck, and total dam with Class A concrete or elastomeric concrete,
- Full depth removal of the dam with Class A concrete,
- Sealant removal and replacement with a:
    - Closed Cell Foam Compression Seal (CCF),
    - Open Cell Compression Seal (OCS),
    - V-Seal (VS), or
    - 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 can be determined. 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 can be created. Before simulating, some adjustment must be made to the data collected in the field.

Some of the costs 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 impact of smaller cut-out dimensions. This reduces the influence of anomalies witnessed during the case study to the rates and values determined and as such are more generally applicable to other studies.

4.5.1 Partial Depth Simulation

The following section provides 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 provides 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); and
- While using Class A concrete or Elastomeric Concrete.

Partial Depth Adjustments for Simulations

Asphaltic plug joints (APJ) were considered for implementation; however, after consulting with a DelDOT representative, 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 APJ joints should not be used. APJ will therefore not be considered in the simulations.

According to the NCHRP 319 study and confirmed by other bridge repair professionals, 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, which is 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 in 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 sand and airblasted to clear it from foreign particles so that the new concrete may bond properly to the steel reinforcement and in-place concrete. As can be seen in Figure 20, 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. 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 loose 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 on the 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 0.625 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)	0.625	0.625
Width (ft)	1.00	1.50
Length (ft)	39.4	39.4
Volume (ft^3)	24.6	37.0

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/worker-hr of effective work, as determined from the case study; thus the effective duration to remove the backwall is 12.4 worker-hours and the total effective duration to partially remove the deck is 18.7 worker-hours. With an idling efficiency of 41.7% associated with the laborers tasked with breaking, the expected duration to partially remove the backwall and deck headers is 17.6 and 26.4 worker-hours, respectively, totaling 44 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 are 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, and are 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 subject to both sides of the dam.

Table 46: Effective (Eff) and Expected (Exp) Durations (Drtn) Associated with Backwall, Deck, and Total Dam Partial Depth Replacement in worker-hors (W-hr)

Stage	Index	Task	Tool	Applicant	Component's Element	Index Dependencies	**Backwall**	**Deck**	**Backwall**	**Deck**
							Eff.Drtn. (W-hr)	Eff.Drtn.(W-hr)	Exp.Drtn (W-hr)	Exp.Drtn (W-hr)
Demo.	1	Concrete Sawing	Handheld Saw	-	Concrete	-	-	-	-	-
Demo.	2	Breaking	TPB	-	Concrete	1(C)	12.4	18.7	17.6	26.4
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)	72.0	72.0	72.0	72.0
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 0.42 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-hr, to complete a partial depth replacement of the backwall, deck, and both headers (the dam) are provided in Table 47.

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

Total Durations Expected (Worker-hr)			
Stage/Task	Backwall	Deck	Dam
Demolition	17.6	26.4	44.0
Curing	78.4	72.0	78.4
Construction	4.45	3.83	8.28
Cleaning	1.18	2.45	3.63
Total Expected Duration (W-hr)	102	105	134

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.

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	11.9	1	6	7.50	11.9	1
Cg.	3	1	12.9	13.3	1	1	12.9	13.4	1
Cg.	4	1	13.3	13.4	1	1	13.4	13.7	1
Const.	5	2	13.4	14.7	1	-	-	-	-
Const.	6	1	14.7	14.7	1	1	13.7	13.7	1
Const.	7	-	-	-	-	-	-	-	-
Const.	8	1	14.7	14.9	1	1	13.7	14.1	1
Const.	9	1	14.7	14.8	1	1	14.1	14.3	1
Const.	10	3	14.9	15.3	1	3	14.3	15.1	1
Const.	11	1	15.3	15.3	1	1	15.1	15.2	1
Const.	12	1	15.3	15.4	1	1	15.2	15.3	1
Const.	13	1	15.4	15.4	1	1	15.3	15.3	1
Const.	14	1	15.4	15.5	1	1	15.3	15.4	1
Const.	15	-	15.5(1)	15.5(3)	3	-	15.4(1)	15.4(3)	3
Const.	16	1	15.5	15.8	3	-	-	-	-
Const.	17	1	15.8	15.8	3	-	-	-	-
Const.	18	1	15.8	16.0	3	-	-	-	-
Const.	19	-	16.0	16.4	3	-	-	-	-
Const.	20	1	16.4	16.5	3	-	-	-	-
Const.	21	-	16.5	22.5	3	-	-	-	-
Cg.	22	2	23.5	23.8	3	2	15.4	16.2	3

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 simultaneously. 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.

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 are 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	$2,579	4.20%
	Fuel Costs	$35.1		
	Material Costs	$1,251		
Road User Costs	Vehicle Operating Cost	$19,100	$57,164	93.0%
	Passenger Delay Costs	$38,064		
Environmental Costs	On-Site Power Source Env. Cost	$54.6	$1,705	2.78%
	Vehicular Env. Cost	$1,651		
Total Cost		$61,449		

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	$2,747	5.34%
	Fuel Costs	$43.5		
	Material Costs	$1,024		
Road User Costs	Vehicle Operating Cost	$15,778	$47,230	91.9%
	Passenger Delay Costs	$31,452		
Environmental Costs	On-Site Power Source Env. Cost	$56.3	$1,420	2.76%
	Vehicular Env. Cost	$1,364		
Total Cost		$51,397		

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 by 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 define the duration of time of expected lane closure, and that side's vehicle operating, passenger delay, and environmental costs 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 are provided in Table 51.

Note that the total cost of the partial dam removal differs by $2,803 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), represent 80 to 95% of the total costs.

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	$2,972	$5,326	8.29%
	Fuel Costs	$78.6		
	Material Costs	$2,275		
Road User Costs	Vehicle Operating Cost	$19,100	$57,164	89.0%
	Passenger Delay Costs	$38,064		
Environmental Costs	On-Site Power Source Env. Cost	$111	$1,762	2.74%
	Vehicular Env. Cost	$1,651		
Total Cost			$64,251	

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 in 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 is not considered as a possible substitute for Class A concrete based on the feedback from the inspectors and contractors that its life expectancy is short. Elastomeric concrete is only considered as a substitute for Class A concrete during partial depth replacements. The simulated costs to implement a partial depth removal of the entire dam, with elastomeric concrete, are shown in Table 52. Thus, the only costs affected are 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	$1,293	$2,579	11.6%
	Fuel Costs	$35.1		
	Material Costs	$1,252		
Road User Costs	Vehicle Operating Cost	$6,354	$19,021	85.7%
	Passenger Delay Costs	$12,668		
Environmental Costs	On-Site Power Source Env. Cost	$54.6	$604	2.72%
	Vehicular Env. Cost	$549.4		
Total Cost		$22,205		

The replacement of the sealant between the armoring may be subject to removal and replacement depending on the assessment of the sealant. As previously mentioned, the sealants included in the 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 necessary. 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, are discussed before simulations over the remaining life of the bridge are provided to determine the most optimal joint maintenance program for Edgemoor Road.

4.5.2 Sealant Replacement Simulation.

Different sealant types were selected and simulated for reconstruction, life expectancy and material costs. The focus of comparison was sealant implementation between the armoring and all related costs for this process. 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. (inches)
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 are thus those that accommodate 3 inches of movement and can be adhered to steel armoring. The sealants considered in the study are the following:

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

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. Four workers will be necessary to complete the seal removal and implementation, one of which is the foreman, two of which are laborers, and one of which is the carpenter, regardless of the sealant chosen. It is recommended that four of the workers be kept from the fourth shift or that the workers laboring under Phase 2 to supplement the four 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 is 3.64 hours or 3 hours and 38 minutes. 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, although an adhesive is used, can support 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 costs and road user environmental impacts.

Table 54: Strip Seal Implementation and Airblasting Duration

Stage	Task	Tool	Component's Element	Bridge Component	Index Dependence	Effective Duration (W-hr)	Workers	Expected Duration (Hr)
Const.	Placing	By Hand	Armoring	Dam	57(C)	10.9	3	3.64
Cg.	Airblasting	Airblaster	Debris	All	58(C)	1.02	1	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 sealant company 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 two-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	Task	Tool	Component's Element	Bridge Component	Index Dependence	Effective Duration (W-hr)	Workers	Expected Duration (hr)
Const.	Placing	By Hand	Armoring	Dam	57(C)	0.50	3.00	0.50
Cg.	Airblasting	Airblaster	Debris	All	58(C)	1.02	1.00	1.02
Crng.	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 five 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 two 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	Task	Tool	Component's Element	Bridge Component	Index Dependence	Effective Duration (W-hr)	Workers	Expected Duration (hr)
Const.	Placing	By Hand	Armoring	Dam	57(C)	0.50	3	0.50
Cg.	Airblasting	Airblaster	Debris	All	58(C)	1.02	1	1.02
Crng.	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 affects 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	14.0	17.6	2671
OCS	2.50	15.0	17.5	2085
VS and CCF	8.50	10.0	18.5	5331

Upon determining sealants to be considered in the simulations, there were two factors that deemed the 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 affect owner, environmental, and societal impacts incurred due to the replacement of the previous sealant and the implementation of a new one. The cost per linear foot of the sealant affects the owner cost only and is inconsequential when compared to the costs incurred through wages and the road user costs; for example, in this case study, the total cost of the strip seal was $546 while the road user cost, for the duration of the case-study, was $516,483. 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 ($/ft)	Cost of Adhesive ($/ft)	Total Cost of Sealant ($/ft)	Comments
CCF	D.S.Brown	CEVA	6.50	1.10	7.60	Cost of adhesive provided by manufacturer representative
SS	D.S.Brown	Steelflex	15.0	0.01	15.0	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 are provided in Table 59. The influence of each sealant's life expectancy upon new construction and rehabilitation is not a factor in Table 59.

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	$155	$883	Owner Costs	Wage Costs	$555	$1,101
	Fuel Costs	-			Fuel Costs	-	
	Material Costs	$728			Material Costs	$547	
Road User Costs	Vehicle Operating Cost	$1,512	$4,540	Road User Costs	Vehicle Operating Cost	$1,937	$5,810
	Passenger Delay Costs	$3,028			Passenger Delay Costs	$3,873	
Environmental Costs	On-Site Power Source Env. Cost	-	$131	Environmental Costs	On-Site Power Source Env. Cost	-	$168
	Vehicular Env. Cost	$131			Vehicular Env. Cost	$168	
Total Cost		$5,554		Total Cost		$7,079	
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	$155	$432	Owner Costs	Wage Costs	$155	$1,247
	Fuel Costs	-			Fuel Costs	-	
	Material Costs	$277			Material Costs	$1,092	
Road User Costs	Vehicle Operating Cost	$4,175	$12,506	Road User Costs	Vehicle Operating Cost	$4,175	$12,506
	Passenger Delay Costs	$8,330			Passenger Delay Costs	$8,330	
Environmental Costs	On-Site Power Source Env. Cost	-	$361.16	Environmental Costs	On-Site Power Source Env. Cost	-	$361
	Vehicular Env. Cost	$361			Vehicular Env. Cost	$361	
Total Cost		$13,298		Total Cost		$14,114	

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 are 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. 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 (2014) 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.

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

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 cannot be recommended, 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 are not 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 to make the values provided more applicable to other projects. As previously mentioned, a 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 to remove 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. Although the parapet face could be partially removed, according to the inspector and based on the infield 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 a rare issue specific to Edgemoor Road that must be dealt with by those providing joint replacement/rehabilitation services and therefore is not included as an operation in 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 from observations during the case study period and based on the experience of the professionals consulted.

- A full depth removal is intended to go through the full depth of concrete. The armoring system is thus assumed to have been welded to the beams.

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

Full Depth Adjustments for Simulations

The durations and rates attained from the case study regarding the backwall are not modified in the full depth removal simulation. Anything relating to the parapet or wing walls are not included in the simulation and all durations associated or dependent on the deck header dimensions, in any way, are 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 the inclusion of an armoring system in the simulations. To conclude, 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 on 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 are 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 consists of 5 days of continuous work, 24-hours a day with 8-hour work shifts. 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 are adjusted for the full depth replacement. There is only one pour and one period of construction. There is only one event of pouring of concrete into the dam, parapet base, and parapet body to reduce the amount of curing time. 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 37.7 ft, 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

Full Depth Work Schedule and Total Costs

Table 62 in this section is 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 provide the duration of each task throughout the duration of the project. The tasks are organized into shifts to take into account the number of workers laboring in each shift, depending on what tasks are to be provided for each shift, in order to optimize the number of crew members in the field to finish the tasks as quickly as possible and reduce overhead costs of wages. The intent of the following schedules is to complete all tasks that are dependent on the work-force to reduce the time until concrete and adhesives need to wet-cure, which, again, are incurred durations that the work-force cannot control. 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 are determined for the full depth header replacement. Calculated in the same manner as the case study 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	$21,162	19.1%
	Fuel Costs	$193		
	Material Costs	$11,608		
Road User Costs	Vehicle Operating Cost	$29,074	$87,007	78.4%
	Passenger Delay Costs	$57,933		
Environmental Costs	On-Site Power Source Env. Cost	$330	$2,842	2.56%
	Vehicular Env. Cost	$2,512		
Total Cost		$111,010		

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, produces a total cost of $111,010, a difference of $459,018 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. Taking into account costs to road users can result in vastly different scheduling of operations than what was observed in the field for the case study.

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 first 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 begin with the adjusted full depth removal of the southern expansion joint during phase 1, where a full depth removal of the headers is 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 were chosen for Edgemoor Road, was dependent on the years remaining of the bridge. The bridge was designed to have a service life of 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 is considered to conclude in 2040 for simplification. Thus, the bridge has a remaining service life of 25 years from the beginning of July 1, 2015.

The 2009 DelDOT Pontis^{TM} system deterioration inventory (DelDOT, 2009) 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 are 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	DN
2 to 10	4.00	12	DN, Rpr&Pro
25 (=<)	2.00	14	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.

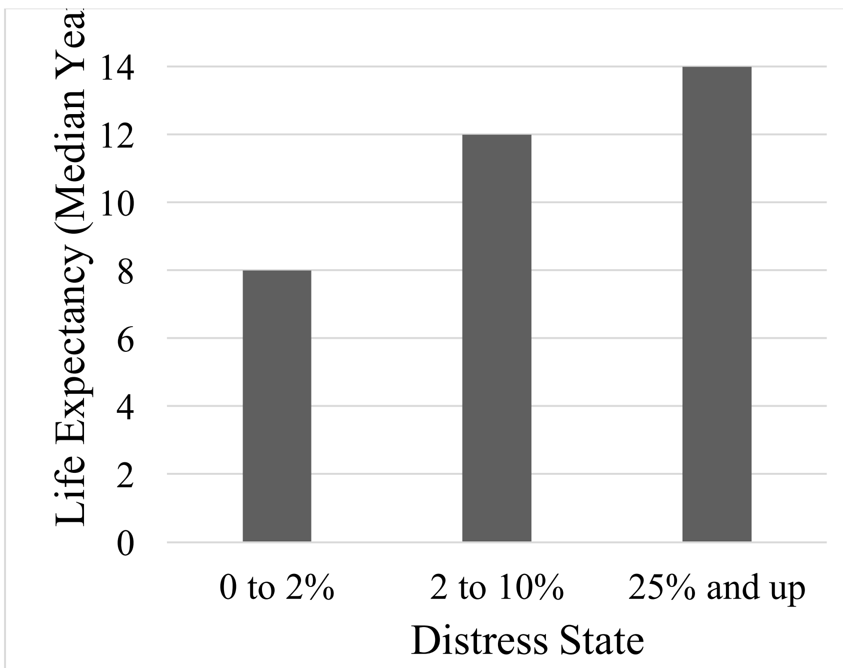


Figure 23: Distress State to Life Expectancy of Concrete Bridge Deck, Used to Model Backwall and Deck Headers

Thus, it is assumed that there is 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 subject 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 are 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 are 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 bring the structure back to 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 nine 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 in Massachusetts (Scott A. Civjan & Brooke Quinn, n.d.). Thus, elastomeric concrete is assumed to have a lifetime of 3 years. 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 (yr)

	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.

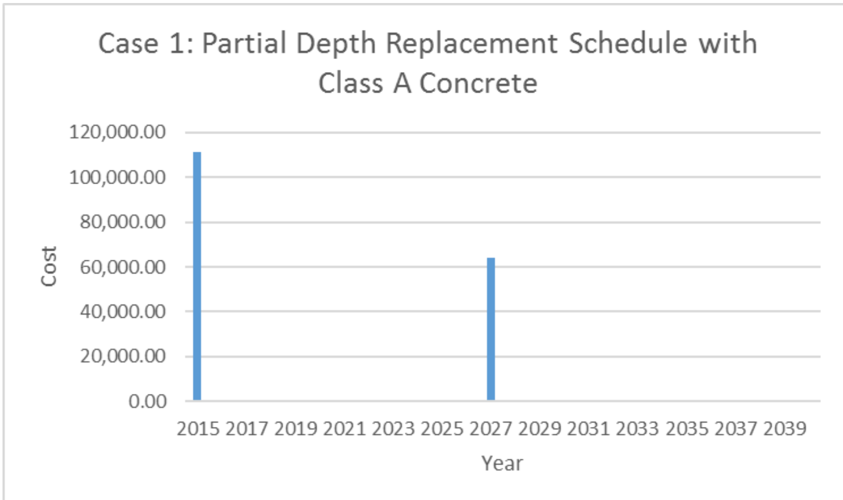
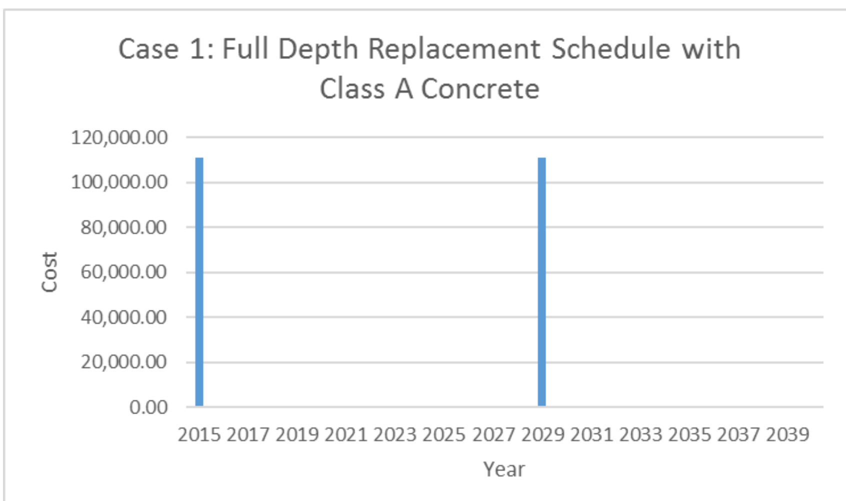
Joint Header Optimized Schedule

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. Clearly, significant uncertainty exists when determining this type of replacement. This approach provides a simplified way to consider alternatives. In the future, probabilistic deterioration modeling could be used to do a sensitivity analysis of suggested solutions on the performance life left.

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 initial condition of the headers and provides it with 14 extra years until it would have to replaced again in 2041, one 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, two 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 rather than waiting until 2029 to provide a full depth replacement. Referring to the previous simulations, a partial depth and full depth replacement would cost $175,262 and $222,021, respectively. Thus, when comparing 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 save $46,759.

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 $22,205, $42,047 cheaper than using Class A concrete for a partial depth replacement, and $88,806 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, which is $91,181 more expensive than providing a partial depth replacement with Class A concrete, and therefore $44,422 more expensive than a full depth replacement. Figure 24 and Table 65 provide the graphical and numerical comparisons for the proposed maintenance schedule and their associated costs for each header.

	**Total Cost= $175,262**
	Total Cost= $222,021

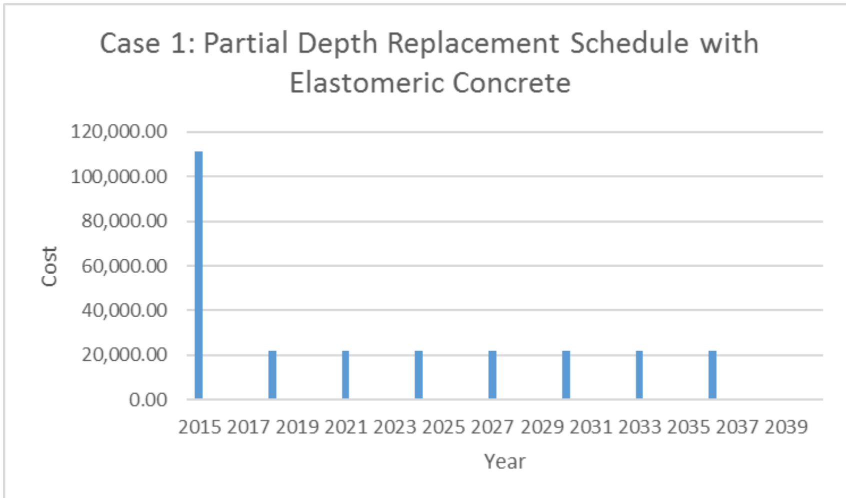
	Total Cost= $266,443

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

Table 65: Joint Maintenance Schedule Costing Scenarios

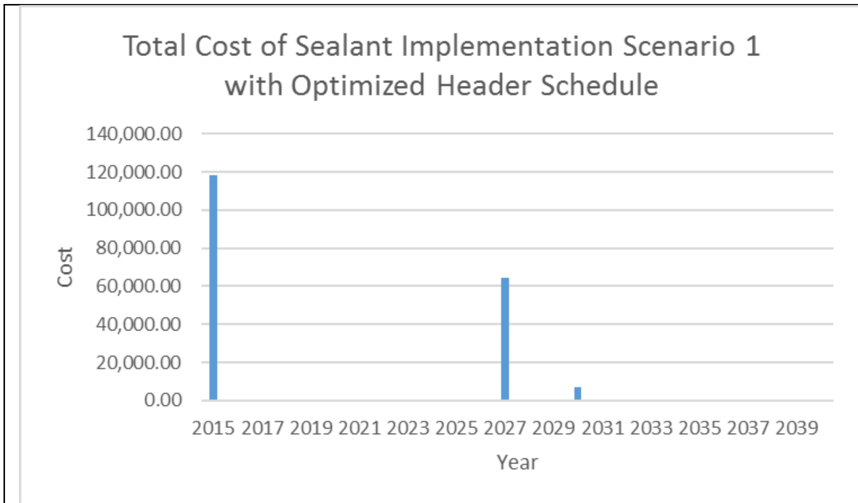
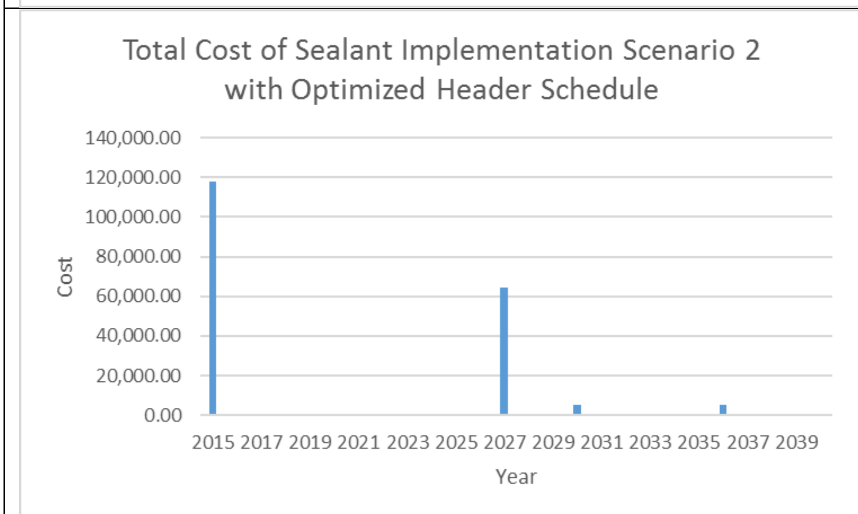
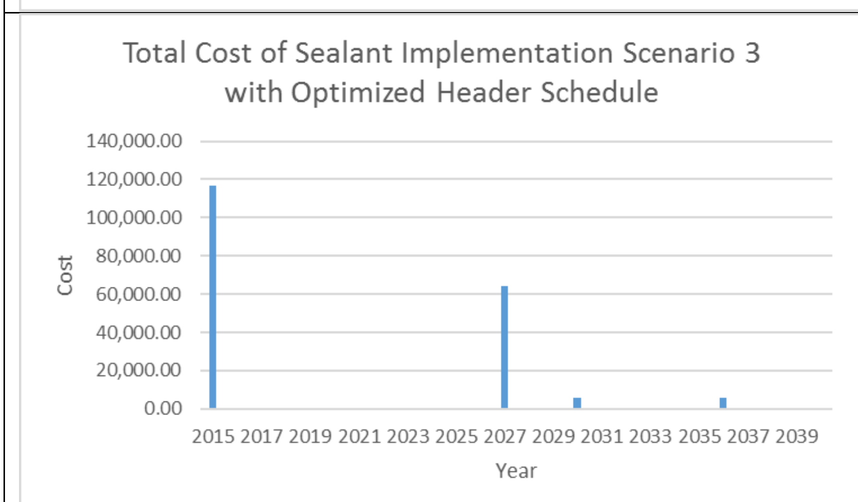
Scheduling Scenario	Cost
Full Depth Replacements	$222,021
Partial Depth Replacements with Class A Concrete Cost	$175,262
Partial Depth Replacements with Elastomeric Concrete Cost	$266,442

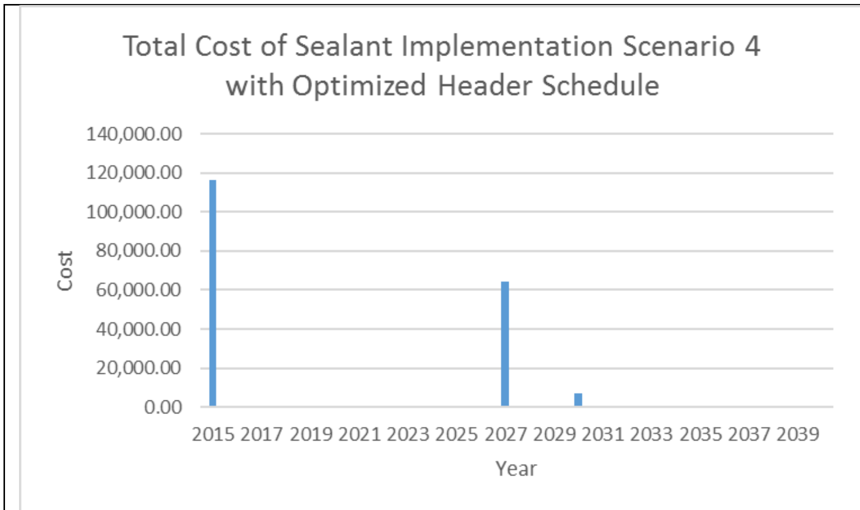
Thus, the most cost efficient option with regards to the agency, societal, and environmental costs, is to have fully replaced the concrete headers in 2015 and partially replace the concrete headers with Class A concrete in 2027.

Joint Sealant Optimized Schedule

Since there is only one full depth replacement during the year of 2015, sealants only have a life expectancy associated with "new construction" once; all other sealant replacements are therefore 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 are not recommendable as the SS and OCS are both cheaper and embody a longer life expectancy than the CCF and VS. There are four possible combinations the way 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 four 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 are shown, graphically and numerically, in Figure 25 and Table 66, comparing the total costs of the four header/sealant combinations. Note that the first costs in 2015, in all four simulations, are a combination of both the full depth removal and the optional sealant implementations. All other costs in the remaining three 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
	**<u>Sealant Scenario (2):</u>** • SS (New) • OCS (Rehab)**X2** **<u>Total Cost=</u>** $193,449
	**<u>Sealant Scenario (3):</u>** • OCS (New) • OCS (Rehab)**X2** **<u>Total Cost=</u>** $191,924



Sealant Scenario (4):

- OCS (New)
- SS (Rehab)

Total Cost=
$187,895

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	SS(New), SS(Rep)	189,420
2	SS(New), OCS(Rep)X2	193,449
3	OCS(New), OCS(Rep)X2	191,924
4	OCS(New), SS(Rep)	187,895

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 for the remaining life of the bridge structure template.

The life expectancies of the OCSs are comparable to those of the SS although 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 $1,525, 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 and 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 possess 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 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 $175,262 and $222,021, respectively. Thus, when comparing 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 $46,759.

By considering the total owner, societal, and environment costs or A+B+C costs, the schedules were accelerated to reduce the societal costs i.e. 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, a difference of $459,018 of the total cost of the case study.

The partial depth replacement using elastomeric concrete 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 rather temporary. On larger roadways where contractors are not allowed limitless time to complete their tasks, the contractors have used such admixtures due to the time limit of lane closures imposed on them. 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 costs to partially demolish and replace concrete with elastomeric headers are much lower but in the long run it can become much costlier. It was calculated that the holistic costs to implement the elastomeric concrete during a partial depth replacement once, is $22,205, $42,047 cheaper than using Class A concrete for a partial depth replacement, and $88,806 cheaper than a full depth removal. However, the holistic costs over the remaining life of the bridge utilizing elastomeric concrete would come out to $266,443, $91,181 more expensive than providing a partial depth replacement with Class A concrete, and therefore $44,422 more expensive than a full depth replacement. Although it is a positive sign that DOT's consider the effects of lane closures on certain roadways, it is likely 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 in 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	Full Depth	Sealant Replacement (Average)	Average	Standard Deviation
Owner Cost	6.67%	8.29%	11.6%	15.7%	10.6%	2.52%
Societal Costs	90.6%	89.0%	85.7%	81.9%	86.8%	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 10.6%, 86.8%, 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 as dominant in the simulation as they were in the case study, and the environmental costs were as low. 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.

Through this evaluation the societal (road-user) costs are so much larger than the owner and environment costs. If user and environmental costing are to be implemented in future projects, the issue of how to scale said costs is of concern. The environmental impacts in this study were greatly underestimated because emissions to water and soil were neglected and a variety of damage categories were ignored. Assigning a cost to environmental impacts is inherently difficult and value laden (Martinez-Alier, Munda, and O'Neill, 1998). This research was only showing that environmental costs could be incorporated into this type of evaluation. More research is needed to evaluate all of the relevant environmental impacts to see the extent of damages caused and to use costing parameters for these impacts that receive a broad base of support. In addition certain owner costs were also similarly neglected.

However, this research shows that considering the total sustainability impacts to owners, users, and the environment of bridge maintenance and repair projects through an A+B+C costing approach is possible. By working towards implementing an A+B+C bidding process, a DOT can incorporate these additional societal and environmental concerns into their contracts and ultimately on the ground during repair work. Utilizing A+B+C costing and bidding together at the DOT level will allow greater accountability for social and environmental impacts that are often overlooked by current bidding and compensation practices today. Additionally, implementing such a system will result in different scheduling of operations for maintenance and repair, ultimately resulting in more sustainable – quicker and more efficient - and less damaging maintenance and repair of bridges. Changing the bidding and costing processes for contractors changes what these projects are optimized for, which incentivizes DOTS and contractors to follow sustainable maintenance and construction practices.

One of the main barriers to this type of A+B+C costing approach is lack of relevant life cycle inventory information about the environmental and human health impacts of bridge maintenance and repair operations. In addition environmental monitoring of the resultant environmental and human health impacts created by traffic due to the presence of a work-zone is also needed.

Sustainable strategies and construction, such as those suggested in this report, circumvent the undesired consequences incurred to society and the environment through traditional construction practices. It is in the public's best interest to reduce road-user delays, vehicle operating costs, and environmental emissions. It is in the interest of serving the public to work towards documenting such costs rigorously and minimizing the impacts of these costs over the life time of a structure. Alternative construction practices that minimize the long term costs to road users are in the best interest of DOT and the public.

BMSs need expansion to support the user costs, environmental costs, and owner costs for bridge elements, 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, although 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 study of life cycle impacts or simplified LCA, such as the one created in by this research, a life cycle inventory more elaborate than needed for LCCA is required. Such a detailed inventory is necessary in any LCA approach due to the environmental and societal impacts of the study that must be evaluated. 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 accuracy and breadth of the assembled inventory.

Chapter 6

SUMMARY & CONCLUSIONS

Based on the durations and rates attained from the case study, optimized full depth, partial depth, and sealant replacement schedules were simulated and the owner, societal, and environment impacts and costs were estimated. After the schedules of the various maintenance actions were determined and life expectancies of all header and sealant types considered, an optimized schedule for future maintenance actions for the abutment expansion joint could be simulated. The type of sealant and whether it would 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;
- Newly implemented strip seal newly after the full depth replacement and removal of the open compression seal; and
- Replacement of the strip seal with an open compression seal in 2030 for a total joint maintenance cost of $187,895.

The most expensive joint maintenance program includes a full depth removal of the headers in 2015, and seven partial depth replacements 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, which is 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. These results support the cost effectiveness of preventive maintenance for bridge joints a trend that is growing amongst agencies today. The results support that it is most cost effective to understand how elements deteriorate and provide services that retard deterioration before major construction or rehabilitation is necessary.

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 should 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.

Bidding processes for maintenance, repair, and replacement projects can use the A+B+C costing method to estimate the costs to owners, users, and the environment.

This research effort acquired data from construction sites to record holistic costs for use in sustainable decision-making with regards to bridge expansion joints in BMSs. 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 ACTION 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 constitute 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. Figure 26 shows the dam headers before, during, and after demolition, and Figure 27 depicts the parapet and wingwall also before, during, and after the demolitions stage.

(a) (b) (c)

Figure: 26-28: Dam Demolition Progression from (a) Pre-Demolition, (b) after 4 Days of Demolition to (3) Pre-Construction Ready

(a) (b) (c)

Figure 27: Parapet and Wing Wall Demolition Progression from (a) Pre-Demolition, (b) Demolition of the Parapet, to (c) 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 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 28.

Figure 28: Pre-Construction, Deck Header Segmentation Through Concrete Saw Cutting with the Walk-Behind-Saw

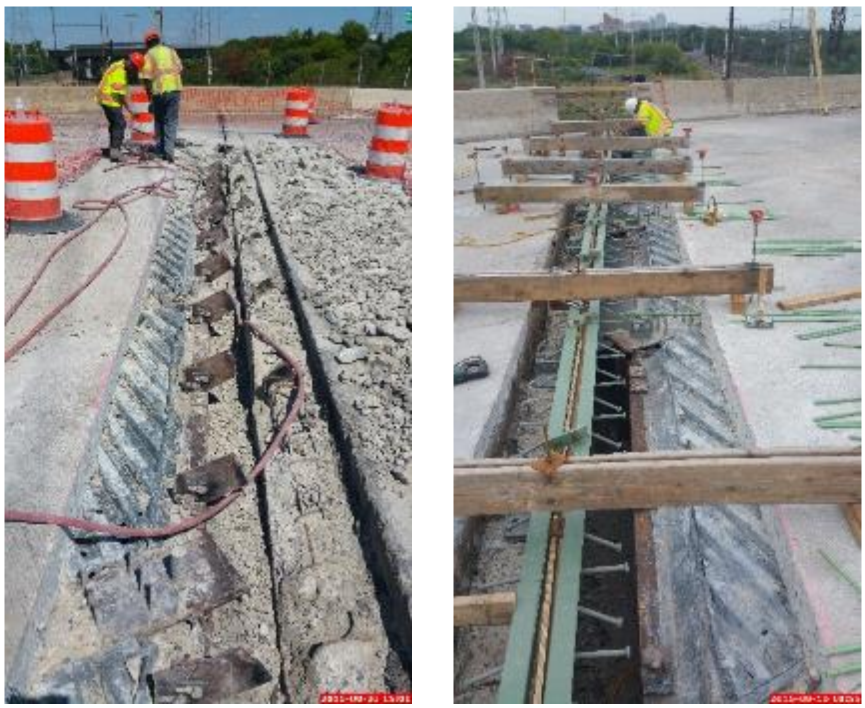
A.1 Dam

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 as shown in Figure 29.

(a) (b)

Figure 29: Depiction of the Poor Physical Condition of the Backwall (a) Prior to Demolition and (b) Excavated by a Shovel

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 epoxied 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.



(a) (b)

Figure 30: The Reversal of the Anchorage Arrangements from Erection of the Bridge to Reconstruction of the Expansion Joint and Headers -Depiction of Deck Header (10) and Backwall (5) Anchorages Arrangements from (a) Previous Construction and (b) During the Construction Stage

In the construction stage of phase 1, 10 anchorage systems were welded to the beams on the deck side of the dam and five anchorage systems were drilled and epoxied into the abutment seat as can be seen in Figure 30. The previous sealant already had detached and was easily spliced and removed from the joint reservoir as can be seen in Figure 31.

Figure 31: 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 Figure 37 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 37.

(a) (b) (c)

Figure 37: Armoring including (a) Heat Cutting/Torching of the Armoring, (b) Segmented Armoring, (with Torch), Momentarily to be Detached when Banged with Breaker and (c) Removal of Armoring with Skid Steer Loader

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 38. Formwork contains the wet concrete and keeps it from spilling out of the designated area of intended pouring until it dries.


Figure 38: 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 39: 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 40. 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 41.

Figure 40: The Skid Steer Loader Breaking on the Deck Header While 30-Pound Breakers Are Utilized on the Backwall

Figure 41: 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

Although 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, subject to breaking by both the 30 pound breakers as well as the skidder as can be seen in Figures 42-43.

Figure 42: Parapet Body Subjected to Breaking from Skid-Steer-Loader

Figure 43: 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

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 dailyly, 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 in 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
w-hr	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

provided as the quotient when determining the completion, or demolition, rate during this stage and the dividend was determined to be 56.6 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 16.1 ft/w-hr.

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 69 provides all demolition tasks, in general order of completion, with their associated durations, and completion rates. 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 does 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 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 (w-hr)	Rate	Unit
Demo.	1	Sawing	Walk Behind Saw	Concrete	Dam	-	0.80	53.64	ft/w-hr
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/w-hr
Demo.	4	Breaking	Skidder	Concrete	Deck	1(C)	4.31	10.8	CF/w-hr
Demo.	5	Breaking	TPB	Concrete	Deck	4 (I)	12.08	1.98	CF/w-hr
Demo.	6	Breaking	Skidder	Concrete	Parapet Body	5(I)	0.17	131	CF/w-hr
Demo.	7	Breaking	TPB	Concrete	Parapet Base + Wing Wall Volume	6 (C)	2.52	6.83	CF/w-hr
Demo.	8	Excavating	By Hand	Rubble	Dam	3(I), 4(I)	9.03	17.6	CF/w-hr
Demo.	9	Torching	Torch	Steel Reinforcement+ Form Removal		3(I)	3.52	16.1	LF/w-hr
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	22.2	Unt/w-hr
Demo.	12	Smoothing	Grinder	Diaphragm	Superstructure	12(C),13(C)	1.00	39.4	ft/w-hr
Demo.	13	Removing	Saw	Strip Seal	Dam	-	0.02	Cnsmbl	Cnsmbl

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	42.9	ft	Walk Behind Saw
Demo.	2	Sawing	Handheld Saw	Concrete	Cnsmbl	Cnsmbl	Cnsmbl	Handheld Saw
Demo.	3	Breaking	TPB	Concrete	Bw Volume Demo'd	49.3	ft^3	Air Compressor
Demo.	4	Breaking	Skidder	Concrete	Deck Volume Demo'd	46.6	ft^3	Skidder
Demo.	5	Breaking	TPB	Concrete	Deck Volume Remaining After Skidder	23.9	ft^3	Air Compressor
Demo.	6	Breaking	Skidder	Concrete	Total Parapet Body Volume	21.8	ft^3	Skidder
Demo.	7	Breaking	TPB	Concrete	Total Demolished Parapet Base and Wing Wall Volume	17.2	ft^3	Air Compressor
Demo.	8	Excavating	By Hand	Rubble	Total Demolished Dam Volume	159	ft^3	-
Demo.	9	Torching	Torch	Steel Reinforcement+ Form Removal	Metal Formwork+ Armoring+ Anchorage(Deck)+ Brackets	56.6	ft	Torch
Demo.	10	Removing	By Hand	Rebar	Cnsmbl	Cnsmbl	Cnsmbl	-
Demo.	11	Smoothing	Grinder	Beam	Exposed Beams	10.0	Beams	Electric Generator
Demo.	12	Smoothing	Grinder	Diaphragm	Exposed Diaphragm Length	39.4	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 lasted for 19 days During the 12 work-days of construction, a total of 233 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.

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	78.7	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	48.7	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 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.

The following discussions provided for the two periods comprising the construction stage are for supplementing and clarifying the values provided in Tables 72, 73, 74, and 75, which 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 39.4 ft, the length upon which the concrete was to be poured was 36.4 ft. 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 36.4 feet, but 39.4 feet of concrete and 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 44.

Figure 44: 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 to pour 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, are referred to as dowels as can be seen in Figure 48. The dowels, anchored into the concrete, support other types of steel reinforcement that in turn supports the poured concrete. Such reinforcements supported by the dowels are the stirrups (seen in Figure 45) and steel reinforcement bars that run laterally along the length of the demolished length of the dam which are referred to simply as rebars (seen in Figure 46). 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 45. Rebars and stirrups are what provides reinforcement to the concrete bridge. Due to the 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 onto which the rebars are tied to, keeping all of the steel reinforcement in place relative to one another while providing shear strength.

Figure 45: Highlighted in Orange is a Dowel Epoxied into the Deck Wall; Highlighted in Yellow is a Stirrup Tied to its Corresponding Dowel.

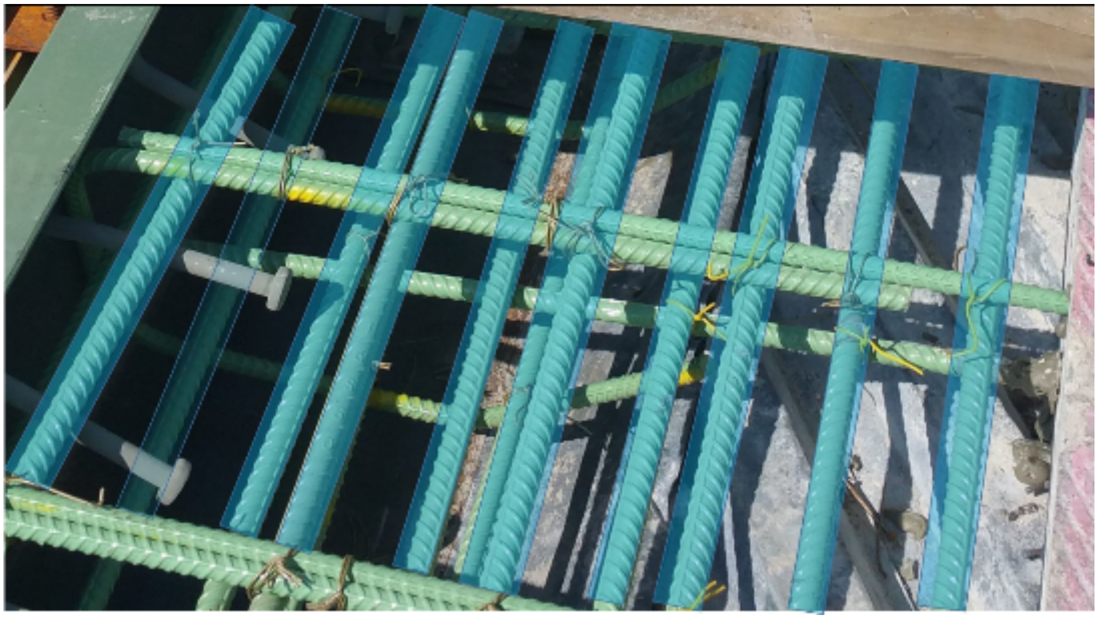


Figure 46: Highlighted in Blue are the Rebars, that are Visible, Running Laterally Along the Demolition Length of the Dam

The dowels were initially fitted for sizing purposes. The fitting was complimented with sawing and resizing of the dowels to fit properly as 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 47c. 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.

(a) (b) (c)

Figure 47: Fitting of the Rebars into the Deck (a) Drilling of the holes for the Dowels, (b) Adjusting the Rebar Length to Fit, and the (c) Placement of the Dowels After the Implementation of the New Armoring System

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 the 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 Figure 48. 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 49.

(a) (b)

Figure 48: The Placement and Adjustment of the Armoring System in the Dam (a) via Skidder and (b) Adjustment of the Armoring System in Dam by Hand

Figure 49: 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 50. 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, six rebars were drilled and epoxied into the depth of the wing wall (vertically), two were drilled and epoxied, longitudinally, into the existing wing wall (horizontally), and eight 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 50: 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 Figure 51, 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.

(a) (b)

Figure 51: The Implementation of the Wooden Formwork for the Backwall Along the Length of the Dam, Formwork (a) Nailed into the Abutment, Underneath the Bridge from the Catwalk and (b) Inbetween the Armoring

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 52. 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 52: The Metal Formwork Running Along the Pouring Length of the Dam, Connected to the Diaphragm and Bottom Lip of the Armoring

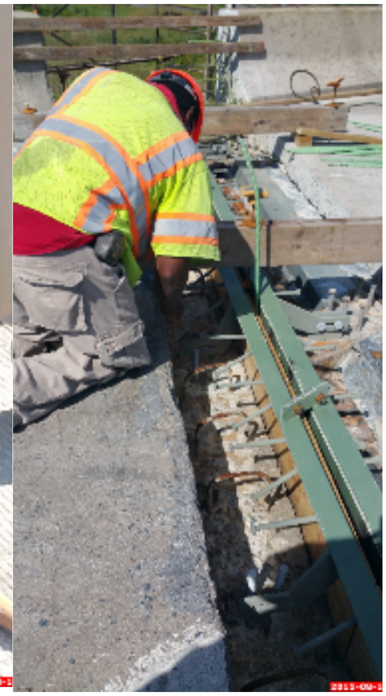
Once the steel, and wooden formwork were constructed, the motor driven welder was delivered to the site. The anchorage on the deck header side of the dam was to be welded to the diaphragm (5 in total) while backwall side anchorage systems were to be drilled and epoxied into the abutment seat (as no metallic 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 53 shows the armoring pieces being welded 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 53. 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 53: Welding of the Two Separately Delivered and Implemented Armoring Systems to One Another

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 the perimeter, between the first and second row of the epoxied dowels and encased within the stirrups. Figure 54 shows the workers placing and tying all steel reinforcement within the deck header. It was assumed that 13 individual pieces of rebar, of 36.4 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.





(a) (b) (c)

Figure: 61-63: The Backwall Anchorage System including (a) Drilling of Anchorage Holes in the Backwall, (b) Pouring of Grout into Holes, and (c) Placement of the Anchorage Component into the Holes with Grout

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 four individual rebar pieces that ran laterally from the parapet to where to bulkhead would be implemented, also seen in Figure 55.

Figure 54: Implementation of the Stirrups and Rebars Through Tying

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 impede 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.

Figure 55: The Cork Formwork Can Be Seen Along the Backwall-Approach Riding Surface Interface, Parallel to the Newly Implemented Rebars

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. A concrete truck arrived on the site and pouring began as seen in Figure 56. 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

(a) (b)

Figure 56: Preparing the Headers Before Pouring of the Concrete (a) Spraying of the Adhesive Spray and (b) During the Pouring with a Mechanical Vibrator Placed Within the Newly Poured Concrete to Facilitate Dissemination of the Concrete

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 57. 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 Figure 58.

Figure 57: The Smoothing of the Newly Poured Concrete Paired with the Spraying of the Curing Compound

© (b) (c)

Figure: 69-71: Water tank (a) and (b) placement of the Wet Burlap, Weeper Hose, and (c) Plastic Tarp atop of the Newly Poured Concrete to Assist in Curing

All task descriptions, durations, dependencies and rates of the first period are included in Tables 72 and 73. It is important that such values are tabulated so that the reader can become more familiar with the tasks incurred in 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 (W-hr)	Rate	Unit
Const.	18	Drilling	Drill	-	Rebar	Deck	17(C)	7.33	9.95	Unt/W-hr
Const.	19	Sawing	Grinder	Rebar	-	Deck	18(C)	2.08	35.0	Unt/W-hr
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/W-hr
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	30.0	Unt/W-hr
Const.	27	Drilling	Drill	Anchorage	Abutment Seat	Backwall	26(C)	1.98	10.1	Unt/W-hr
Const.	28	Sawing	Saw	Wood	Formwork	Backwall	23(C)	1.33	27.3	ft/W-hr
Const.	29	Sawing	Grinder	Metal	Formwork	Deck	23(C)	8.77	4.15	ft/W-hr
Const.	30	Drilling	Drill	-	Rebar	Wing Wall	23(C)	0.63	12.6	Unt/W-hr
Const.	31	Placing	By Hand	Wood	Formwork	Backwall/ Dam	28(C)	5.15	7.07	ft/W-hr
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	34.6	ft/W-hr
Const.	36	Placing	By Hand	Anchorage	Abutment Seat	Backwall	27(C)	1.50	6.67	Unt/W-hr
Const.	37	Placing	By Hand	Rebar+Stirrups	-	Deck	29(C)	16.12	2.45	ft/W-hr
Const.	38	Repositioning	By Hand	Bracket	-	Backwall	-	0.62	Cnsmbl	Cnsmbl
Const.	39	Placing	By Hand	Rebar	-	Backwall	27(C)	4.70	8.39	ft/W-hr

Const.	40	Placing	By Hand	Rebar	-	Wing Wall	30(C)	2.90	5.52	Unt/W-hr
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	21.9	ft/W-hr
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	ft^2/W-hr
Const.	46	Pouring	Concrete Truck	Wet Concrete	-	Dam and Pp Base (Deck)	45(C)	0.57	204.6	CF/W-hr
Const.	47	Shoveling	By Hand	Wet Concrete	-	Dam and Pp Base (Deck)	46(I)	1.13	102.3	CF/W-hr
Const.	48	Vibrating	Vibrator	-	Wet Concrete	Dam and Pp Base (Deck)	46(I)	0.57	204.6	CF/W-hr
Const.	49	Smoothing	By Hand	-	Wet Concrete	Dam and Pp Base (Deck)	48(C)	2.90	45.41	ft^2/W-hr
Const.	50	Spraying	By Hand	Curing Compound	Wet Concrete	Dam and Pp Base (Deck)	49(C)	0.07	1975	ft^2/W-hr
Const.	51	Placing	By Hand	Burlap	Wet Concrete	Dam and Pp Base (Deck)	51(C)	0.27	143	ft/W-hr
Const.	52	Placing	By Hand	Weeper Hose	Wet Concrete	Dam and Pp Base (Deck)	51(C)	0.07	575	ft/W-hr
Const.	53	Placing	By Hand	Tarp	Wet Concrete	Dam and Pp Base (Deck)	52(C)	0.07	575	ft/W-hr

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	73.0	Rebar	Electric Generator
Const.	19	Grinder	Rebar	-	Dowels	73.0	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	11.0	Attachments	Electric Generator
Const.	25	Drill	-	Armoring System Support	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	26	By Hand	-	Anchorage	Brackets	15.0	Brackets	-
Const.	27	Drill	Anchorage	Abutment Seat	Anchrg Holes	20.0	Holes	Electric Generator
Const.	28	Saw	Wood	Formwork	Const+Pp Length	36.4	ft	Saw
Const.	29	Grinder	Metal	Formwork	Pouring Length	36.4	ft	Electric Generator
Const.	30	Drill	-	Rebar	Wing Wall Holes	8.00	Holes	Electric Generator
Const.	31	By Hand	Wood	Formwork	Pouring Length	36.4	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)	53.1	ft	Engine Driven Welder
Const.	36	By Hand	Anchorage	Abutment Seat	Brackets	10.0	Brackets	-

Const.	37	By Hand	Rebar+Stirrups	-	Const. Length	39.4	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	132	ft^2	-
Const.	46	Concrete Truck	Wet Concrete	-	Total Dam and Pp Base (Deck) Volume	116	ft^3	Concrete Truck
Const.	47	By Hand	Wet Concrete	-	Total Dam and Pp Base (Deck) Volume	116	ft^3	-
Const.	48	Vibrator	-	Wet Concrete	Total Dam and Pp Base (Deck) Volume	116	ft^3	Electric Generator
Const.	49	By Hand	-	Wet Concrete	Total Dam and Pp Base (Deck) Surface Area	132	ft^2	-
Const.	50	By Hand	Curing Compound	Wet Concrete	Total Dam and Pp Base (Deck) Surface Area	132	ft^2	-
Const.	51	By Hand	Burlap	Wet Concrete	Dam and Pp (Deck) Length	38.3	ft	-
Const.	52	By Hand	Weeper Hose	Wet Concrete	Dam and Pp (Deck) Length	38.3	ft	-
Const.	53	By Hand	Tarp	Wet Concrete	Dam and Pp (Deck) Length	38.3	ft	-

B.2 Period 2

The second period of the construction stage can be generalized as the segment 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 wingwall 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 wingwall 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 59. A total of eight and six 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.

Figure 59: Formwork of the Wing Wall and Parapet Base

After the formwork was finished, the wing wall and base were prepped with sprayed adhesive pre-pouring, then subjected to shoveling and vibrating of the concrete during the pouring. This was followed by smoothing, spraying of the curing compound, and application of wet burlap, weeping hose and tarp, to assist in the curing process, procedurally in the same manner as for the dam as can be seen in Figure 60.

Figure 60: 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 61. 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. Afterwards, the parapet bodies were subject to the same pre-pouring, pouring, then curing techniques observed in the other two pours that occurred.

Figure 61: 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 62. 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 63. The total concrete pouring and partial reconstruction occurred from the parapet fascia through the eastbound direction roadway to its interface with the median. The completed dam and parapet can be seen in Figure 64.

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

Figure 62: Application of Silicone Within the Backwall and Approach Riding Surface Interface, Above the Cork Formwork

Figure 63: Implementation of the Strip Seal Extrusion into the Armoring

Figure 64: Depiction of Replaced Headers of Lane 1 and the Parapet Resulting from Completion of the Case-Study

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 (W-hr)	Rate	Unit
Const.	54	Placing	By Hand	Stirrups	-	Parapet Body	40(C)	4.23	3.31	Unt/W-hr
Const.	55	Placing	Drill	Wood	Formwork	Wing Wall Fascia	54(C)	4.50	Cnsmbl	Cnsmbl
Const.	56	Placing	Drill	Wood	Formwork	Parapet Base Fascia	55(I)	2.00	Cnsmbl	Cnsmbl
Const.	57	Spraying	By Hand	Concrete Adhesive	-	Wing Wall/ Parapet Base (Bw)	56(C)	0.03	202	ft^2/W-hr
Const.	58	Pouring	Concrete Truck	Wet Concrete	-	Wing Wall/ Parapet Base (Bw)	57(C)	0.23	50.9	ft^3/W-hr
Const.	59	Vibrating	Vibrator	Wet Concrete	-	Wing Wall/ Parapet Base (Bw)	58(C)	0.35	33.9	ft^3/W-hr
Const.	60	Smoothing	By Hand	-	Wet Concrete	Wing Wall/ Parapet Base (Bw)	59(C)	0.30	22.4	ft^2/W-hr
Const.	61	Spraying	By Hand	Curing Compound	Wet Concrete	Wing Wall/ Parapet Base (Bw)	60(C)	0.02	404	ft^2/W-hr
Const.	62	Placing	By Hand	Burlap	Wet Concrete	Wing Wall/ Parapet Base (Bw)	61(C)	0.03	202	ft^2/W-hr
Const.	63	Placing	Drill/ Saw	Wood	Formwork	Parapet Body	54(C)	15.1	Cnsmbl	Cnsmbl
Const.	64	Spraying	By Hand	Insulating Foam Sealant	Formwork	Parapet Body	63(C)	0.25	159	ft^2/W-hr
Const.	65	Spraying	By Hand	Concrete Adhesive	-	Parapet Body	64(C)	0.02	658	ft^2/W-hr
Const.	66	Pouring	Concrete Truck	Wet Concrete	-	Parapet Body	65(C)	0.33	65.4	ft^3/W-hr
Const.	67	Shoveling	By Hand	Wet Concrete	-	Parapet Body	66(C)	0.33	65.4	ft^3/W-hr
Const.	68	Vibrating	Vibrator	-	Wet Concrete	Parapet Body	67(C)	0.33	65.4	ft^3/W-hr
Const.	69	Smoothing	By Hand	-	Wet Concrete	Parapet Body	68(C)	0.42	14.5	ft^2/W-hr
Const.	70	Spraying	By Hand	Curing Compound	Wet Concrete	Parapet Body	69(C)	0.03	181	ft^2/W-hr
Const.	71	Grinding	Grinder	Cork	Formwork	Backwall	53(C)	0.20	182	ft/W-hr
Const.	72	Applying	By Hand	Primer	Cork	Backwall	71(C)	0.05	728	ft/W-hr
Const.	73	Pouring	AT 1200 S	Silicone	-	Backwall	72(C)	0.15	243	ft/W-hr
Const.	74	Applying	By Hand	Methacrylate	-	Backwall	73(C)	0.08	450	ft/W-hr
Const.	75	Placing	By Hand	Strip Seal Extrusion	Armoring	Dam	53(C)+CrngTim	19.67	1.85	ft/W-hr

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	Placing	By Hand	Stirrups	-	Stirrups	14.00	Stirrupts	-
Const.	55	Placing	Drill	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	56	Placing	Drill	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator
Const.	57	Spraying	By Hand	Concrete Adhesive	-	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	58	Pouring	Concrete Truck	Wet Concrete	-	Wing Wall/ Parapet Base(Bw) Volume	11.9	ft^3	Concrete Truck
Const.	59	Vibrating	Vibrator	Wet Concrete	-	Wing Wall/ Parapet Base(Bw) Volume	11.9	ft^3	Electric Generator
Const.	60	Smoothing	By Hand	-	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	61	Spraying	By Hand	Curing Compound	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	62	Placing	By Hand	Burlap	Wet Concrete	Wing Wall/ Parapet Base(Bw) Surface Area	6.73	ft^2	-
Const.	63	Placing	Drill/ Saw	Wood	Formwork	Cnsmbl	Cnsmbl	Cnsmbl	Electric Generator

Const.	64	Spraying	By Hand	Insulating Foam Sealant	Formwork	Total Parapet Body Area Encasement	39.7	ft^2	-
Const.	65	Spraying	By Hand	Concrete Adhesive	-	Total Parapet Body Surface Area of Bases	11.0	ft^2	-
Const.	66	Pouring	Concrete Truck	Wet Concrete	-	Total Parapet Body Volume	21.8	ft^3	Concrete Truck
Const.	67	Shoveling	By Hand	Wet Concrete	-	Total Parapet Body Volume	21.8	ft^3	-
Const.	68	Vibrating	Vibrator	-	Wet Concrete	Total Parapet Body Volume	21.8	ft^3	Electric Generator
Const.	69	Smoothing	By Hand	-	Wet Concrete	Total Parapet Body Top Surface Area (Top)	6.03	ft^2	-
Const.	70	Spraying	By Hand	Curing Compound	Wet Concrete	Total Parapet Body Top Surface Area (Top)	6.03	ft^2	-
Const.	71	Grinding	Grinder	Cork	Formwork	Pouring Length	36.4	ft	Electric Generator
Const.	72	Applying	By Hand	Primer	Cork	Pouring Length	36.4	ft	-
Const.	73	Pouring	AT 1200 S	Silicone	-	Pouring Length	36.4	ft	Air Compressor
Const.	74	Applying	By Hand	Methacrylate	-	Pouring Length	36.4	ft	Air Compressor
Const.	75	Placing	By Hand	Strip Seal Extrusion	Armoring	Pouring Length	36.4	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 64) 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 65) and at the end of the phase. Sandblasting was employed to abrasively clean the concrete surfaces from foreign debris 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 Figure 66), 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 0.97 hours of the total sandblasting duration occurred intermittently during the end of the demolition stage and 0.75 of constant airblasting occurred at the end of Phase 1, along with airblasting, for a final cleaning of the deck.

Figure 64: An Example of One of the Many Intermittent Airblasting Session at the End of the First Day of the Demolition Stage

Figure 65: An Example of an Intermittent Sandblasting Session in the Dam In-Between the Placement of the Rebars in the Deck and Backwall Headers

(a) (b)

Figure 66: Grinding of Newly Formed Concrete on (a) Roadway Parapet Face and (b) Parapet Base Fascia

The following tasks were observed in the relative order tabulated below in Table 76. A faux index is 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: 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	68.5	ft^3/ W-hr
Cg.	B	Collecting	By Hand	Rubble	Dam	3(I)	28.3	5.62	ft^3/ W-hr
Cg.	C	Collecting	Skidder	Rubble	Dam	3(I)	5.03	31.6	ft^3/ W-hr
Cg.	D	Sandblasting	Sandblaster	Rubble	Dam	6(C)	0.97	164	ft^3/ W-hr
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	40.0	Unt/W-hr
Cg.	G	Smoothing	Grinder	Concrete	Dam	53(C)	1.58	80.5	ft^2/ W-hr
Cg.	H	Smoothing	Grinder	Concrete	Parapet Body	70(C)	2.25	17.7	ft^2/ W-hr
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 76 represents a list of unique tasks performed on the bridge for cleaning with their associated bridge components, the 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 ft^3/w-hr. 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 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	159	ft^3	Air Compressor
Cg.	B	Collecting	By Hand	Rubble	Total Volume Demolished	159	ft^3	-
Cg.	C	Collecting	Skidder	Rubble	Total Volume Demolished	159	ft^3	Skidder
Cg.	D	Sandblasting	Sandblaster	Rubble	Total Volume Demolished	159	ft^3	Air Compressor
Cg.	E	Collecting	By Hand	Rubble	Cnsmbl	Cnsmbl	Cnsmbl	-
Cg.	F	Vacuuming	Vacuum	Drilled Hole Debris	Anchrg Holes	20.0	Holes	Electric Generator
Cg.	G	Smoothing	Grinder	Concrete	Dam Surface Area	127	ft^2	Electric Generator
Cg.	H	Smoothing	Grinder	Concrete	Parapet Body Surface Area	39.7	ft^2	Electric Generator
Cg.	I	Sandblasting	Sandblaster	Rubble	Cnsmbl	Cnsmbl	Cnsmbl	Air Compressor

Cg.	J	Airblasting	Airblaster	Debris	Cnsmbl	Cnsmbl	Cnsmb l	Air Compresso r

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 in 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	22.50
Electricians	62.10
Iron Workers	42.20
Laborers	33.01
Millwrights	16.11
Painters	60.64
Piledrivers	66.42
Power Equipment Operators	41.18
Sheet Metal Workers	22.75
Truck Drivers	33.90

The workers on the crew for the Edgemoor Road Southern abutment joint replacement, laborers, heavy equipment operators, carpenters, and foremen, were each assumed to be a specific type of worker in Table 78. Table 79 provides the total number of worker-hours spent by each worker type, and the associated wages incurred to the owner to pay each worker-type.

The carpenter and skidder operator were similar in their efficiency, which was, on average, 71.5%. The laborers, however, had an efficiency of 51.2%, or 20.3% less than the average efficiency of the carpenter and skidder operator, shown in Table 81. Of course no one can be 100% efficient while working and everyone is mandated by law to take breaks. Due to scheduling and timing of many tasks, on any job workers sometimes wait for a task to be completed before being able to start or finish another task. It should be noted that such a large difference in efficiencies between types of workers 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.

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.

As can be seen in Table 83, of the total wages to be paid by the owner of, $19,645, 34.8% or $6,842, went towards idling. Figure 15 provides the total costs, including the idling and effective costs on a daily basis throughout the phase.

Table 79: Total Workers on the Field, and the Corresponding Work-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	7.00	14.0	0.00	0.00	0.00	302	462	0.00	0.00	0.00	764
7/31	7.00	23.0	0.00	5.00	0.00	302	767	0.00	157	0.00	1,226
8/3	7.00	35.0	0.00	0.00	0.00	302	1,155	0.00	0.00	0.00	1,457
8/4	7.00	28.0	0.00	0.00	0.00	302	924	0.00	0.00	0.00	1,226
8/5	7.00	42.0	0.00	0.00	0.00	302	1,386	0.00	0.00	0.00	1,688
8/6	7.00	26.0	0.00	2.00	0.00	302	843	0.00	80.9	0.00	1,226.
8/7	7.00	34.0	0.00	1.00	0.00	302	1,117	0.00	38.0	0.00	1,457
8/10	7.00	42.0	0.00	0.00	0.00	302	1,380	0.00	6.60	0.00	1,688
8/13	12.0	21.0	0.00	0.00	2.00	538	693	0.00	0.00	66.2	1,297
8/14	7.00	28.0	7.00	0.00	0.00	302.	924	302	0.00	0.00	1,528
8/17	7.00	21.0	7.00	0.00	0.00	302	693	302	0.00	0.00	1,297
8/18	7.00	11.0	0.00	1.00	0.00	302	363	0.00	16.5	0.00	682
8/19	4.50	17.6	0.00	0.00	0.00	194	580	0.00	13.8	0.00	788
8/20	5.30	15.8	0.00	0.00	0.00	227	520	0.00	0.00	0.00	746
8/21	7.00	13.0	0.00	3.00	0.00	302	49	0.00	91.3	0.00	82
8/24	9.00	28.5	0.00	2.00	0.00	388	941	0.00	68.8	0.00	1,398
8/25	2.30	4.60	2.30	0.00	0.00	99.3	1,52	99.3	0.00	0.00	350

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

Date	Supervision(f)	f	l	ca	p	w	Total Effective Durations (w-hr)	Idling Duration (w-hr)	Efficiency
7/30	7.00	0.00	9.45	0.00	0.00	0.00	17.3	3.75	82.1
7/31	7.00	1.63	13.8	0.00	4.48	0.00	25.3	9.72	72.2
8/3	7.00	0.00	15.4	0.00	0.00	0.00	22.4	19.6	53.3
8/4	7.00	0.67	12.7	0.00	0.00	0.00	19.7	15.3	56.3
8/5	7.00	0.48	31.7	0.00	0.00	0.00	38.7	10.3	79.0
8/6	7.00	0.53	9.77	0.00	1.68	0.00	18.5	16.6	52.7
8/7	7.00	0.20	10.5	0.00	1.03	0.00	18.5	23.5	44.0
8/10	7.00	0.00	12.4	0.00	0.20	0.00	19.6	29.4	40.0
8/13	12.5	0.00	13.0	0.00	0.00	1.53	27.0	8.00	77.1
8/14	7.00	0.00	14.3	5.37	0.00	0.00	26.7	15.3	63.5
8/17	7.00	0.00	9.70	4.62	0.00	0.00	21.9	13.1	62.5
8/18	7.00	0.00	4.50	0.00	0.50	0.00	12.0	6.50	64.9
8/19	4.50	0.00	9.03	0.00	0.42	0.00	14.2	8.33	63.0
8/20	5.25	0.00	15.1	0.00	0.00	0.00	20.4	0.65	96.9
8/21	7.00	0.00	3.80	0.00	1.43	0.00	12.6	10.2	55.2
8/24	9.00	0.00	19.8	0.00	0.33	0.00	29.1	10.5	73.5
8/25	2.30	0.00	1.83	1.83	0.00	0.00	5.97	3.23	64.9

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	

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

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 used. 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, rebars, 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 adhesive 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. 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 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	$/ft	2.00	Ft/W-hr	-	-	36.41	ft	$546.17
Strip Seal Armoring	Strip Seal Armoring, 3" Movement (Both Sides)	RPS Machinery-DS Brown-Ackerman and Baynes	$182.00	$/ft	7.12	Ft/W-hr	-	-	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

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 ($)	Unit	Initial Usage Rate	Unit	Usage Rate Conversion	Unit	Usage Amount	Unit	Total Cost ($)
Sandblasting	Ebony grit 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 E-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 was 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.

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

$v_r = Traffic\ speed\ during\ roadwork$

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

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

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

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

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

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

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

Equation E-2

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

Similar to the BridgeLCC software-based equation above, 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).

r=Weighted average of vehicle costs

Equation E-3

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

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 was introduced to take into account the costs incurred to cars specifically (Jutila et al., 2007), as shown below

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

o_G = Operating costs for transported goods

o_D = Operating costs for cars

Equation E-4

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

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 count 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 are 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 subject to the coverage count program, adjustment factors have been developed to further adjust AADT values. Adjustment factors have been developed and are tabulated for determining the AADT distribution by hour on weekdays and weekends, known as the daily 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, representing the weekday and weekend DHVs, respectively (*Delaware Vehicle Volume Summary 2014 (Traffic Summary)*, n.d.).

Edgemoor Road falls under TPG 2, the hourly volume and speed throughout the weekdays and weekends of a particular month can be determined. Note that such results are determined for the roadway without a work zone during normal conditions as follows:

- AADT= 8,417 Vehicles per Day;
- % Truck (T)= 9%; and
- Directional Split= 55% in the Primary (Westbound) Direction.

Table 96: 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 daily factors, the distribution of volume throughout a weekday and weekend can be determined. 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 adjusts 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 97: 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	17,799	N/A	16,694	36,523	27,919	25,050	25,050	N/A	17,432	29,351	43,832	26,542	47,020	15,373	18,719	23,042
8	18,082	8,354	15,829	36,759	28,837	25,397	25,397	8,354	17,324	29,104	44,284	26,332	49,112	15,450	18,877	24,019
Month	% AADT															
7	112	N/A	109	102	97.5	99.5	99.5	N/A	110	105	102	100.2	97.6	119	105	99.7
8	114	104	104	102	101	101	101	104	109	104	102.8	99.5	102	120	106	104

By determining the percentage that each MADT represents from the total AADT value, and the average of these percentage values, the MADT factors are determined for Edgemoor Road for the months of July and August.

Table 98: 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 from DelDOT, 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 0.55, while the volume of vehicles eastbound (secondary) direction was determined by performing the dot product of the DHV by 0.45, 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).

Equation E-5

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

Equation E-6

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

Equation E-7

$$AHT_P = (\mathbf{D_P})(\mathbf{DHV})$$

Equation E-8

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

After the volume of vehicles traveling in the primary and secondary direction were calculated, it was 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, was 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 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 99 provides the AHT's for weekdays and weekends during the month of August. The following values were determined by 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 when the work zone was not present at all.

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.

Table 99: 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

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) at green with increasing traffic delays at orange and red and the highest delay at 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 67: Google Map Image and Average Congestion Feature Example (Google Maps, 2016)

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.

Table 100: Color Designation to Speed per Google Maps Traffic Delays

Traveling Speed Assumptions	
Google Maps Traffic Delay Colors	Assumed Traveling Speed (mph)
Green	35.0
Orange	26.3
Red	17.5
Maroon	8.75

After the colors were tabulated, the numerical values from Table 100 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 101.

Table 101: Designated Speeds, without Work-Zone, on Edgemoor Road Eastbound and Westbound Direction During Weekdays and Weekends (Google Maps, 2016)

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

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.

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 102.

Table 102: 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 103, the total amount of grams of each specific pollutant during normal operations on the structure were determined. Table 104 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 103: Emitted Pollutants for Normal Operations on Structure During 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 104: Costs of Emitted Pollutants During Normal Operations on Structure for 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

The case study consisted of a work zone that mandated that the eastbound direction be detoured while two of the three 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 drivers 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 105 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 105: 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 106: 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 F

OPTIMIZED FULL DEPTH REPLACEMENT SCHEDULE

In this section, the assumptions are described that are used for the simulations. The first day and shift solely consists of demolition. The crew consists of nine workers of which one 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 six laborers using 30-pound 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 active. The first shift tasks, durations and schedule are shown in Table 107. 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 107: Demolition Tasks Incurred During the First Day and Shift

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (W-hr)	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 nine workers, including two foremen, six laborers, and one 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 108. 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 108: 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 (W-hr)	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 nine workers, including one foreman and seven laborers and one 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, preparations 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 109. 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 109: 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 (W-hr)	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 three workers, including one foreman and two 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 110 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 110: 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 (W-hr)	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 four workers, one of which is the foreman and two of which are laborers and one of which is the carpenter, regardless of the sealant chosen. It is recommended that four of the workers be kept from the fourth shift or that the workers laboring under Phase 2 supplement the four 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 111 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 112 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 113 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 113 were re-simulated to occur in one day, with a fixed crew of four workers, of which three are laborers and one is the foreman. Such costs will be inconsequential to the road user costs as they are assumed to occur within the phase; the tasks will only affect the owner, and environmental costs due to extra hours worked and operating power sources.

Table 111: 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 (W-hr)	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 112: 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 (W-hr)	Workers	Expected Duration (W-hr)	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 113: Intermittent Cleaning Tasks Incurred Throughout the Duration of the Project

Stage	Index	Task	Tool	Applicant	Component's Element	Bridge Component	Index Dependence	Effective Duration (W-hr)	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