Sustainability of Rural Steel and Concrete Bridges

Prepared For
American Iron & Steel Institute
Short Span Steel Bridge Alliance

By
Dr. Michael Barker, PE
Sarah Bridges
Ione Chandler
Peyton Smith

Civil & Architectural Engineering & Construction Management
University of Wyoming

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The opinions and conclusions in this report are not necessarily those of the American Iron & Steel Institute or the Short Span Steel Bridge Alliance

Executive Summary

The objective of this study is to evaluate the life cycle sustainability (cradle to grave) of two functionally equivalent steel and concrete rural bridges. Both bridges are simple span and located in Whitman County, Washington. The bridges are considered nearly identical in that both bridges have the same outcome where each bridge meets the two-lane rural crossing requirements and the Whitman County bridge crew built both bridges. Only the superstructure of the bridges is considered in this analysis for a direct comparison of rural steel and concrete bridges. A second objective of the work is to develop procedures where the owner or society can consider sustainability benefits in the design of bridges.

Four sustainability criteria were developed to evaluate and compare the sustainability of the two bridges. The criteria include embodied carbon and equipment emissions, embodied and equipment energy consumption, waste management and recyclability, and life cycle cost. The criteria were applied to the construction, maintenance, and demolition life cycle of the bridges.

The results show that, over the life cycle, the concrete bridge (1) results in 26.3% more embodied CO_2e emissions, (2) consumes 8.7% more energy, and (3) recycles 17.8% less material (if the concrete is recycled at all) at the end of the bridge life than the steel bridge. The concrete bridge also has a life cycle cost 23% higher than the steel bridge.

A multi-criteria decision-making analysis was applied to determine the respective benefit-cost ratios for the two bridges. Appropriate weights were applied to each of the normalized sustainability benefits to obtain a final benefit score for the bridges. The sustainability benefit scores (higher are better) are 0.996 for the steel bridge and 0.845 for the concrete bridge. This indicates that the sustainability benefits (emissions, energy consumption and recyclability) of the steel bridge are greater than those of the concrete bridge. The normalized life cycle cost scores (lower is better) are 0.808 for the steel bridge and 1.000 for the concrete bridge. The steel bridge is not only more sustainable, but more economical as well. The resulting benefit cost ratios considering sustainability become 1.226 for the steel bridge and 0.845 for the concrete bridge.

The steel bridge outperforms the concrete bridge for both sustainability and life cycle costs, so the decision on which type bridge to select is clear. However, procedures were developed so that society or the owner can consider sustainability when the decision is not trivial. Sustainable design is predicated on the idea that society is willing to pay extra for reducing harmful effects on the environment. Examples of sustainability benefits would include reduced emissions, reduced energy consumption or higher rates of recyclability. A procedure is presented that considers monetized sustainability benefits for any number of bridge alternatives associated with a bridge project. The owner or society determines an acceptable additional cost they are willing to pay for reducing emissions, reducing energy consumption, or reducing material sent to the landfill. The initial cost, or life cycle cost, of the alternatives is adjusted for the monetary sustainability benefits associated with reducing harmful environmental impacts to determine an equivalent cost that can be compared to select the best alternative.

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1 INTRODUCTION

1.1 Objective of the Study

The objective of this study is to evaluate the life cycle sustainability (cradle to grave) of two nearly identical, functionally equivalent steel and concrete rural bridges. Both bridges are short simple span and located in Whitman County, Washington. The bridges are considered functionally equivalent in that both bridges have the same outcome where each bridge meets the two-lane rural crossing requirements and the Whitman County bridge crew built both bridges. Only the superstructure of the bridges is considered in this analysis for a direct comparison of rural steel and concrete bridges. Lifetime sustainability considers sustainability benchmarks at each phase in the bridge life cycle, including acquisition of the materials, the manufacturing process of bridge components, construction, maintenance, and demolition at the end of the life cycle. A multi-criteria decision-making analysis (MCDA) that considers sustainability and life cycle costs is used to compare the rural steel and concrete bridges.

A second objective of the work is to develop procedures where the owner or society can consider sustainability benefits in the design of bridges.

1.2 Steel Bridge: Seltice-Warner

The steel bridge used is the Seltice-Warner Bridge located in Oakesdale, Washington in Whitman County. The bridge consists of seven rolled beam girders and a corrugated metal deck for a gravel riding surface. The bridge is 35 ft-8 in long, and 28 ft wide, as detailed in Figure 1. The prefabricated modular steel bridge was delivered to the bridge site and the bridge was constructed by the Whitman County bridge crew. The Seltice-Warner bridge was built in 2020. A photo of the superstructure of the Seltice-Warner bridge is shown in Figure 2.

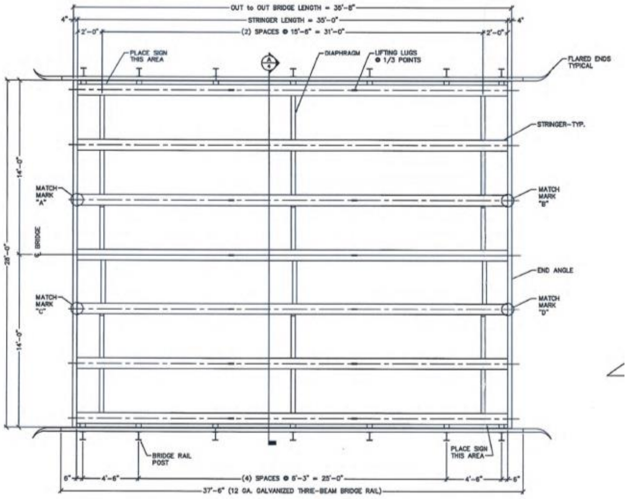


Figure 1: Seltice-Warner Framing Plan

Figure 2: Seltice-Warner Superstructure

1.3 Concrete Bridge: Thornton Depot

The concrete bridge is the Thornton Depot Bridge in Thornton, Washington, also in Whitman County. The bridge consists of eight precast prestressed rectangular girders. The girders themselves are the concrete riding surface. The bridge is 34 ft long, and 32 ft wide. The precast bridge modules were delivered to the bridge site and constructed by the Whitman County bridge crew. The Thornton Depot bridge was built in 2019. The plan is shown in Figure 3 and the superstructure is shown in Figure 4.

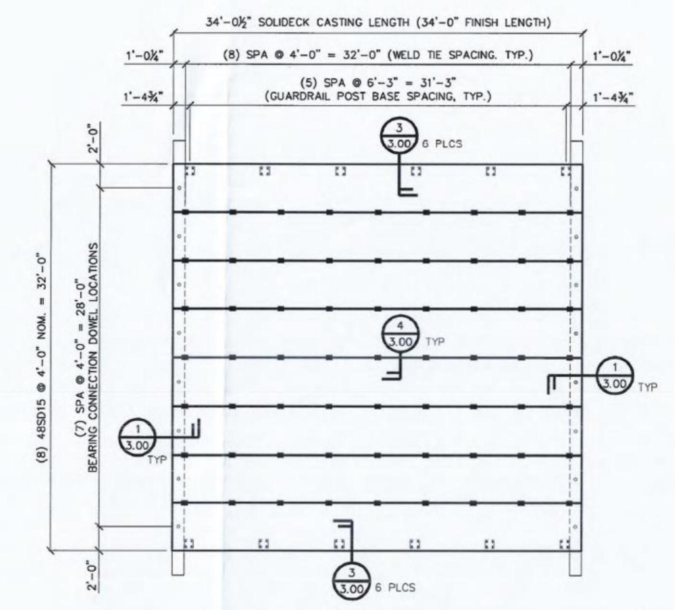


Figure 3: Thornton Depot Framing Plan

Figure 4: Thornton Depot Superstructure

1.4 Summary and Results

To consider sustainability of rural bridges, four sustainability criteria, based on LEED and Envision criteria, have been developed to evaluate and compare the sustainability of the two bridges. The criteria include embodied carbon emissions, which will be referred to simply as emissions in this report, energy consumption, waste management and recyclability, and life cycle costs. Data for each of these four criteria was collected and totaled for each phase in the lifespan of the bridge: construction, maintenance, and demolition. For each bridge, using a simple linear utility function, a normalized benefit value was determined for emissions, energy consumption, and recyclability. A normalized cost was determined for life cycle cost.

A multi-criteria decision-making analysis was applied to determine the respective benefit-cost ratios for the two bridges. Appropriate weights were applied to each of the normalized benefits to obtain final benefit scores for the bridges. The benefit scores (higher are better) are 0.996 for the steel bridge and 0.845 for the concrete bridge. This indicates that the sustainability benefits (emissions, energy consumption and recyclability) of the steel bridge are greater than those of the concrete bridge. The life cycle cost scores (lower is better) are 0.808 for the steel bridge and 1.000 for the concrete bridge. The steel bridge is not only more sustainable, but more economical as well. The benefit score is divided by the normalized life cycle cost to determine a final benefit-cost ratio considering sustainability. The benefit-cost ratio for the steel bridge is 1.226 where it is 0.845 for the concrete bridge.

For the Seltice-Warner steel and the Thornton Depot concrete bridges, the steel bridge outperforms the concrete bridge for both sustainability and life cycle costs, so there is no decision to make to determine the optimal bridge. The decision is straightforward. However, the report develops procedures so that society or the owner can consider sustainability when the decision is not trivial. The idea of considering sustainability in the design of a bridge entails answering the question, “what additional cost would society or the owner be willing to pay to increase sustainability benefits?” Examples of sustainability benefits would include reduced emissions, reduced energy consumption or higher rates of recyclability.

The study considers two “what if” scenarios applied to the two bridges. The first is the sensitivity of the prefabricated steel bridge cost as it relates to initial cost, life cycle cost, and sustainability benefit cost ratio decision making. The second assumes the concrete bridge has the same initial cost as the steel bridge and examines the sustainability benefits gained with the additional cost of the steel bridge. The procedure is framed as reductions in emissions or reduction in energy consumed for every extra dollar spent.

A simple decision-making procedure is presented that considers monetized sustainability benefits for any number of bridge alternatives associated with a bridge project.

2 SUSTAINABILITY CRITERIA FOR RURAL BRIDGES

Several sustainability rating systems were examined and compared to help guide the selection of criteria and benchmarks for the sustainability comparison of the steel and concrete bridges. The sustainability rating systems that influenced the criteria selection for this analysis were LEED and Envision. An overview of each rating system as well as descriptions of the criteria from each rating system that were applicable to this study are discussed below.

2.1 Sustainability Rating Systems for Buildings and Infrastructure

To determine the criteria to be used to analyze the sustainability of rural bridges, existing rating systems for buildings were studied. The benchmarks and criteria used in these rating systems that could apply to the project scope are discussed.

2.1.1 Leadership in Energy and Environmental Design (LEED)

The Leadership in Energy and Environmental Design (LEED) program is a green building rating system that is used around the world. LEED has seven areas of concentration, which include sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation in design process and regional priority. These seven categories are broken down further into benchmarks shown in Figure 5. The LEED rating system pertains to green buildings and communities, so consideration was taken to determine which categories were applicable to bridges. The categories considered in the development of the sustainability criteria for the bridge analysis are Energy and Atmosphere and Materials and Resources.

2.1.1.1 Energy and Atmosphere

The energy and atmosphere category focuses on reducing energy use, CO_2e emissions, and developing an energy efficient design (LEED v4 for Building Design and Construction). Although the bridge itself does not rely on energy for operation, the energy required to construct, maintain, and demolish a bridge over its lifetime is an important measure of sustainability.

2.1.1.2 Materials and Resources

The materials and resources category discusses the minimization of material embodied energy and waste. Material embodied energy includes the energy consumed by material extraction, processing, transport, maintenance, and disposal (LEED v4 for Building Design and Construction). The management and minimization of material waste focuses on material sourcing and disposal.

2.1.2 Envision

Envision is a rating system that encourages sustainable design by providing a set of guidelines used in the preliminary design and planning phases of a project. While LEED provides a set of guidelines for sustainability in buildings, Envision targets infrastructure projects. It is used for many different types of infrastructure projects including “roads, bridges, pipelines, railways, airports, dams, levees, landfills, water treatment systems, and other components that make up civil works" (Envision Sustainable Infrastructure Framework). Envision has 60 sustainability credits that are organized into 5 main categories: quality of life, leadership, resource allocation, natural world, and climate and risk. This information is shown in Figure 5. The categories considered in the development of the sustainability criteria for the bridge analysis are resource allocation and climate and risk.

2.1.2.1 Resource Allocation

Allocating resources is the groundwork for creating fully functioning infrastructure. The quantity, source, and characteristic of resources and their impact on the sustainability of the project are the focus in this category. The three subcategories of resource allocation are materials, energy, and water (Envision Sustainable Infrastructure Framework).

The materials subcategory stresses the importance of decreasing the total amount of materials used in the infrastructure project. By choosing materials that are recycled or recyclable, the number of natural resources consumed for the project can be minimized.

The primary goal of the subcategory energy is to encourage a reduction in overall energy consumption in a project.

Like energy, the subcategory water encourages the reduction of overall water use in infrastructure projects by considering other water sources, like stormwater. This subcategory does not apply to the construction of the steel and concrete bridges.

2.1.2.2 Climate and Risk

Climate and risk addresses two fundamental issues, emissions and the resilience of the project. The emissions and the resilience of the project are evaluated based upon their short-and long-term risks and hazards (Envision Sustainable Infrastructure Framework).

The emissions subcategory promotes the reduction of harmful emissions, such as greenhouse gas and air pollutant emissions, throughout the life cycle of the project.

Resilience focuses on the project's ability to combat short-term risks as well as adjust with changing long-term conditions. Resilience for bridges is not a concern since bridges meet standard safety and performance requirements over their lives.

2.2 Sustainability Rating System for Rural Bridges

The LEED and Envision sustainability rating systems influenced the development of four criteria and subsequent benchmarks for each criterion. The criteria chosen to compare the sustainability of rural concrete and steel bridges are emissions, energy consumption, recyclability and waste management, and life cycle cost. Figure 5 illustrates which criterion from the LEED and Envision rating systems specifically influenced the development of the criteria for the bridge analysis. Each of these criterion have a set of measurable benchmarks that determine the benefit score for a bridge. The LEED or Envision criteria credits attributed to sustainable sites, water efficiency, indoor environmental quality, innovation in design process and regional priority, quality of life, leadership, and natural world were deemed not essential for sustainability of rural county bridges.

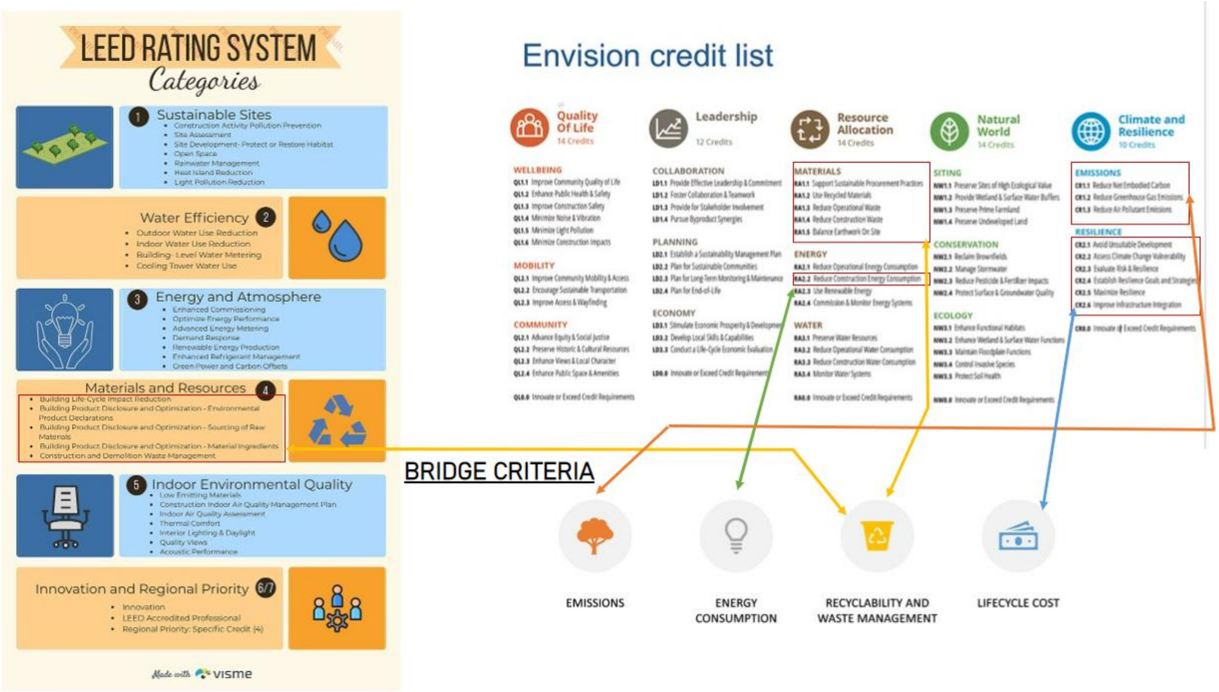


Figure 5: Illustration of criteria selection from LEED and Envision

2.2.1 Emissions

There are four benchmarks that fall under the greenhouse gas emissions criterion. These include emissions produced by material extraction, material production and fabrication of each bridge, and emissions produced during construction, maintenance procedures, and demolition.

The emissions produced by the materials and fabrication are found in Environmental Product Declarations (EPD). EPDs include the total emissions associated with the production of a particular material type or bridge component. Examples include emissions output while producing cement and obtaining aggregates and other materials that are used to fabricate the precast concrete bridge; emissions output producing steel and fabricating the steel bridge; and transportation emissions as the materials are transported to and from the steel and concrete manufacturer's facilities.

Emissions output during construction, maintenance, and demolition result from construction equipment usage. The emissions produced by the diesel fuel burned during the time the equipment is in use can be totaled to reflect the total emissions output for the construction phase, maintenance procedures, and demolition phase separately.

2.2.2 Energy Consumption

Energy consumption considers the same four benchmarks as the emissions criterion, energy consumption during material extraction and fabrication and energy consumption during construction procedures, maintenance, and demolition.

The EPDs used to gather information about the bridge material emissions output also consider the embodied energy of each material or component. As with emissions, examples of embodied energy outputs include energy consumed while producing cement and obtaining aggregates and other materials that are used to fabricate the precast concrete bridge; energy consumed producing steel and fabricating the steel bridge; and transport energy as the materials are transported to and from the steel and concrete manufacturer’s facilities.

The energy consumed by the construction equipment can come from actual and estimated equipment hours during construction, maintenance procedures, and during bridge demolition. The energy consumed is measured from the fuel burned during the time the construction equipment will be running.

2.2.3 Recyclability and Waste Management

Recyclability and Waste Management primarily focuses on two benchmarks, the weight of recyclable material recovered during demolition and the weight of material going to the landfill.

2.2.4 Life Cycle Costs

The life cycle cost criterion includes the life expectancy of the bridges, the initial cost of the bridges, maintenance costs, demolition costs, and the salvage payback of recycling the demolished material or the cost to send material to the landfill. Initial costs for the bridges would consider the total costs for installing the bridge including labor, materials, and equipment. Maintenance costs consider the costs of labor and equipment over the bridge life. Demolition and salvage costs account for the labor and equipment costs of demolition and the salvage payback from the recycling mill for scrap and the costs to discard any steel or concrete into a landfill. The total life cycle cost for each bridge is determined using a Present Value Cost with an appropriate discount rate.

3 SUSTAINABILITY CRITERIA AND BENCHMARKS FOR RURAL BRIDGES

To assess quantitatively the sustainability of rural steel and concrete bridges, the four criteria are applied to the example bridges used in this study. This is accomplished using benchmarks for each criterion. This section discusses three phases of bridge life: construction, maintenance, and demolition, as well as the sustainability benchmarks that apply to the life cycle of the bridges. A variety of sources were used to collect the necessary information for analysis. Whitman County personnel supplied data on costs, construction information and estimations for yearly maintenance and demolition. Whitman County resources were considered for recycling and landfill information and national average recycling rates (AISC, EPA) were applied to both the steel and concrete materials.

Information on specific component emissions and embodied energy is given in product specific Environmental Product Declarations (EPD). These EPDs are generated by companies such as the American Institute of Steel Construction (AISC), the Steel Deck Institute (SDI), and the prestressed concrete manufacturer Clark Pacific. It should be noted that structural bolts and connectors for both bridges are not considered in this analysis because of their small contribution and lack of EPDs. The emissions for equipment usage were based on the amount of greenhouse gas produced every hour the equipment was in use and the energy consumed was based on the energy consumed by diesel fuel used while the equipment was in use. It should also be noted that transportation of the prefabricated bridge, equipment and crew to and from the site during its lifespan is not considered. Therefore, there will be no energy or emissions from transportation. This decision was made to simplify the analysis even though the emissions and energy consumed from transportation may vary between the two bridges, an example being that the steel bridge units are delivered on one truck while the concrete bridge units are delivered on multiple trucks.

3.1 Life Cycle Emissions, Energy Consumption, Recyclability and Waste Management, and Costs

The benchmarks for emissions, energy consumption, recyclability and waste management procedures, and life cycle costs associated with construction, maintenance, and demolition of the bridge are outlined below.

3.1.1 Construction of Superstructure

The first phase of the life cycle is the construction of the bridge superstructure. This includes erecting the prefabricated bridge and the materials, labor, and equipment for the installation.

3.1.1.1 Energy and Emissions

The construction of the superstructure emissions and energy consumed includes the prefabricated bridge components and the construction equipment used to erect the bridge. The emissions and embodied energy are determined for each of the fabricated components that make up the bridge superstructure. Components include precast concrete beams, grout, steel plates and shapes, the steel bridge deck and gravel. The emissions total and the total embodied energy for each of these components are the sum of the emissions produced and energy consumed while obtaining raw materials, manufacturing, fabricating and transporting the materials to and from the manufacturer.

The equipment used during the construction of each bridge was provided by Whitman County, and the emissions output and energy consumed by each piece of equipment used was determined.

3.1.1.2 Costs

The costs of the superstructure construction includes the cost of the prefabricated bridge, materials, construction equipment, and labor to install the bridge. These values were provided by Whitman County.

3.1.2 Maintenance

The second phase of the life cycle is maintenance. The lifespan of each bridge is assumed to be 75 years, with the first 25 years maintenance free and yearly maintenance required for the remaining 50 years. Whitman County provided the average yearly maintenance procedures they believed would be necessary. For the concrete bridge, potential maintenance includes fixing weld ties, sweeping the concrete deck, and fixing any damage to the guardrails. For the steel bridge, potential maintenance includes, road grading, re-graveling, and fixing damaged guardrails. Although maintenance emissions and energy consumed is considered in the analysis, maintenance for the two bridges is assumed to be identical, so no difference in the sustainability assessment will result from maintenance.

3.1.2.1 Equipment Emissions and Energy

Emissions and energy consumed is measured for the equipment used for the bridge maintenance. For both bridges, it is estimated that an average of 3 hours of heavy equipment and 3 hours of light equipment use are necessary per maintenance year.

3.1.2.2 Costs

The cost of maintenance for each bridge is the estimated yearly cost of maintenance over the 50 years. The estimated yearly cost of maintenance is $750 per year where it is divided into $375 for labor and $375 for equipment. These costs become part of the life cycle costs.

3.1.3 Demolition

The last phase for the bridge is demolition of the bridge at the end of its life. The Seltice-Warner bridge demolition process is expected to take 2 days. Demolition of the Thornton Depot bridge is expected to take 4 days.

3.1.3.1 Deconstruction Equipment Emissions and Energy

Emissions and energy consumed is measured for the equipment used during the bridge demolition. Estimates on how long it would take to demolish each bridge were provided by Whitman County. For the Seltice-Warner steel bridge, the estimate is 20 hours of heavy equipment and 15 hours of light equipment are required. The Thornton Depot concrete bridge would require 40 hours of heavy and 20 hours of light equipment.

3.1.3.2 Recyclability and Landfill

At the end of the lifespan of the bridge, it will be dismantled and discarded. The volume of material that will be recycled or dumped in a landfill will be considered for each bridge. According to the American Institute of Steel Construction, 98% of the steel used in a project is recycled at the end of its life. Therefore, the Seltice-Warner bridge is assumed to have 98% of its steel recycled after it has been demolished with the remaining sent to a landfill. According to the Environmental Protection Agency, 66,535,034 tons of concrete is put in landfills each year, while 315,222,966 tons are recycled (Construction and Demolition Debris Management). From this, it can be determined that 82.6% of concrete is recycled from all construction and demolition debris in the US each year. Although Whitman County does not plan to recycle the Thornton Depot bridge, it is assumed to have 82.6% of the concrete and 98% of the steel recycled after it has been demolished for a more favorable comparison to the steel bridge.

3.1.3.3 Costs and Surplus

The labor and equipment costs for demolition were estimated by Whitman County. For the Selitce-Warner bridge, there is an estimated \$5,000 labor cost and \$1,110 equipment cost. For the Thornton Depot bridge, \$7,500 for labor and \$2,040 for equipment. For the discarded materials, there is a fee involved with sending material to a landfill. The Whitman County landfill charges a fee of \$75/ton. There is a salvage payback (benefit) for the recycled steel, but there is still a cost (although less than landfill costs) for recycling the concrete. The Pacific Steel Recycling Mill will pay \$100/ton for steel scrap. However, to recycle the concrete at Pro Recycle LLC in Spokane, Washington, the cost is \$4.10/ton. These costs or salvage benefits become part of the life cycle costs for each bridge.

3.2 Life Cycle Sustainability Metrics

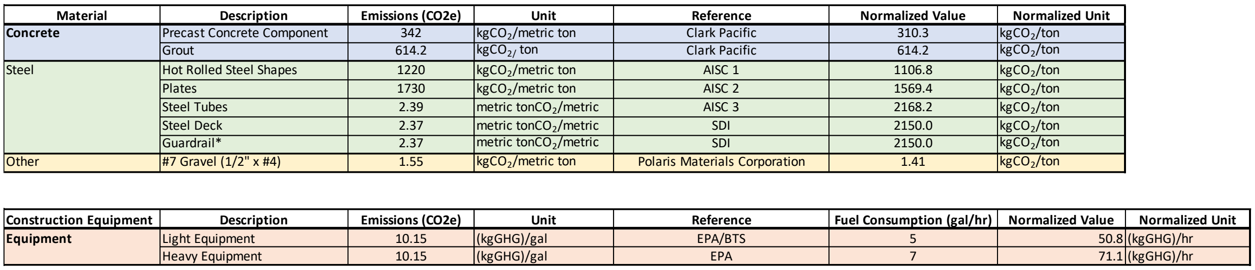
Metrics for emission production and energy consumption are determined from EPDs based on fabricated components and materials in the bridge superstructure. Industry wide EPDs were searched and considered for each component or material to find the "best fit" metrics. For the construction equipment, emission production and energy consumption are based on equipment usage.

The EPDs used for each component measured the kg of CO_2e produced and the MJ of energy consumed based on varying base units. For example, the documents for hot rolled steel shapes and plates measured the emissions in kg of CO_2e per metric ton while the steel tubes and deck EPDs measured the emissions in terms of metric tons of CO_2e per metric ton. These values were normalized to kg of CO_2e per US ton and MJ per US ton for consistent application to the bridges.

The CO_2e metrics for each component are shown in Table 1. The original EPD values and units are recorded in the "Emissions (CO_2e)" and "Unit" columns. The normalized values and units are shown in the "Normalized Value" and "Normalized Unit" columns. A normalized kg of CO$_2$e per hour for the construction equipment is derived. Likewise, the energy consumption metrics for each component are shown in Table 2.

The following sections discuss the EPDs selected for each bridge component and the reasoning for each selection. The EPDs used for the study can be viewed by the links provided in Section 7 References.

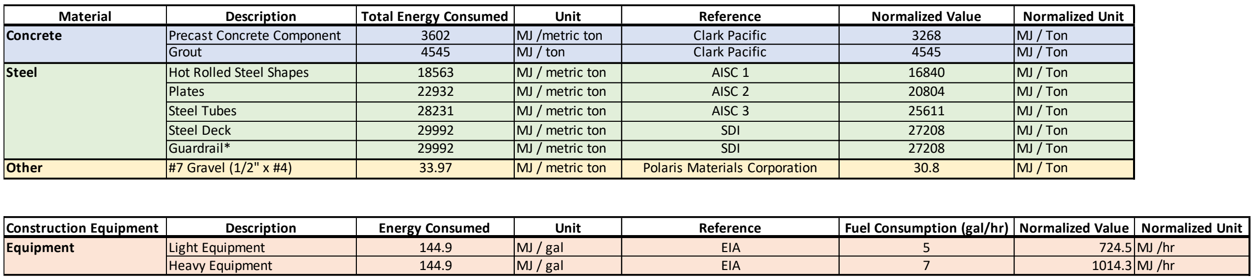
Table 1: Emissions Metrics



Material	Description	Emissions (CO2e)	Unit	Reference	Normalized Value	Normalized Unit
Concrete	Precast Concrete Component	342	kgCO$_2$/metric ton	Clark Pacific	310.3	kgCO$_2$/ton
	Grout	614.2	kgCO$_2$/ ton	Clark Pacific	614.2	kgCO$_2$/ton
Steel	Hot Rolled Steel Shapes	1220	kgCO$_2$/metric ton	AISC 1	1106.8	kgCO$_2$/ton
	Plates	1730	kgCO$_2$/metric ton	AISC 2	1569.4	kgCO$_2$/ton
	Steel Tubes	2.39	metric tonCO$_2$/metric	AISC 3	2168.2	kgCO$_2$/ton
	Steel Deck	2.37	metric tonCO$_2$/metric	SDI	2150.0	kgCO$_2$/ton
	Guardrail*	2.37	metric tonCO$_2$/metric	SDI	2150.0	kgCO$_2$/ton
Other	#7 Gravel (1/2" x #4)	1.55	kgCO$_2$/metric ton	Polaris Materials Corporation	1.41	kgCO$_2$/ton

Construction Equipment	Description	Emissions (CO2e)	Unit	Reference	Fuel Consumption (gal/hr)	Normalized Value	Normalized Unit
Equipment	Light Equipment	10.15	(kgGHG)/gal	EPA/BTS	5	50.8	(kgGHG)/hr
	Heavy Equipment	10.15	(kgGHG)/gal	EPA	7	71.1	(kgGHG)/hr

Table 2: Energy Consumption Metrics



Material	Description	Total Energy Consumed	Unit	Reference	Normalized Value	Normalized Unit
Concrete	Precast Concrete Component	3602	MJ /metric ton	Clark Pacific	3268	MJ / Ton
	Grout	4545	MJ / ton	Clark Pacific	4545	MJ / Ton
Steel	Hot Rolled Steel Shapes	18563	MJ / metric ton	AISC 1	16840	MJ / Ton
	Plates	22932	MJ / metric ton	AISC 2	20804	MJ / Ton
	Steel Tubes	28231	MJ / metric ton	AISC 3	25611	MJ / Ton
	Steel Deck	29992	MJ / metric ton	SDI	27208	MJ / Ton
	Guardrail*	29992	MJ / metric ton	SDI	27208	MJ / Ton
Other	#7 Gravel (1/2" x #4)	33.97	MJ / metric ton	Polaris Materials Corporation	30.8	MJ / Ton

Construction Equipment	Description	Energy Consumed	Unit	Reference	Fuel Consumption (gal/hr)	Normalized Value	Normalized Unit
Equipment	Light Equipment	144.9	MJ / gal	EIA	5	724.5	MJ /hr
	Heavy Equipment	144.9	MJ / gal	EIA	7	1014.3	MJ /hr

3.2.1 Concrete Components

An EPD for a precast concrete structure in Washington developed by Clark Pacific for five different structural precast products was used for the precast beam components for the Thornton Depot bridge (Clark Pacific). Of the five precast products in the EPD, the gravity beam was deemed to be the most structurally representative of the precast bridge girders in the Thornton Depot bridge.

The EPD selected for the concrete bridge grout was from the Tile Council of North America, Inc. (Laticrete). The EPD is intended for cement grout for tile installation but was used because there was a high-strength option available within the EPD. Other grout EPDs were not found, so this was the best option available.

3.2.2 Steel Components

The steel material types that are in the bridges are hot rolled steel shapes, plates, steel tubes, galvanized steel deck, and galvanized guardrail. The EPDs for the hot rolled steel shapes, plates, and steel tubes were produced by the American Institute of Steel construction. The documents provided industry averages for the fabricated products' environmental emissions and energy consumption properties. The Steel Deck Institute provided the EPD for galvanized steel deck. The galvanized guardrail is assumed to be the same material as the galvanized steel deck.

3.2.3 Gravel

The steel bridge has a gravel riding surface. The ASTM certified gravel EPD was produced by Polaris Materials with CO2e emissions and energy consumption metrics.

3.2.4 Construction Equipment

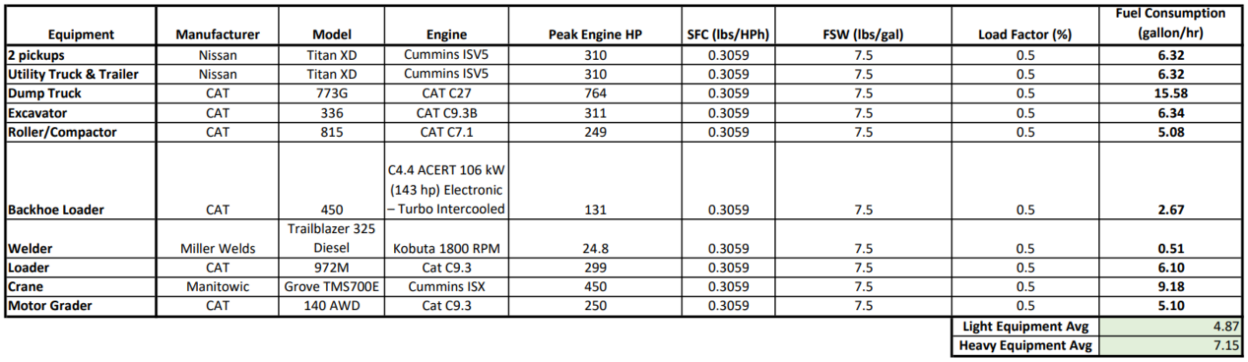
Whitman County provided information about the equipment and materials that were used during the construction of each bridge. Using this information, the equipment emissions outputs and energy consumption values were estimated.

The construction equipment was split into two categories, heavy equipment and light equipment. The heavy equipment consisted of excavators, roller/compactors, backhoes, front-end loaders, cranes, motor graders, and dump trucks. The light equipment included pickup trucks, utility truck and trailers, and welders. To determine the average fuel consumption for the heavy and light equipment, the fuel consumption for each piece of equipment was determined. To calculate the engine fuel consumption in gallons per hour (GPH), an equation relating peak engine horsepower (HP) of the engine, the diesel engine specific fuel consumption, and the diesel engine fuel specific weight was used (Mohan). This is multiplied by a load factor to normalize the fuel consumption of the equipment. Without the load factor, the fuel consumption value would represent how much fuel was consumed while the piece of equipment was operating at peak horsepower. It is rationally assumed that the equipment will be performing at 50% of the load, therefore the gallons of fuel consumed per hour will reflect that decrease from peak power. Equation 1.0 was used to calculate the fuel consumption, GPH, of each piece of equipment:

$$GPH = \frac{Peak\ Engine\ HP * Specific\ Fuel\ Consumption}{Fuel\ Specifc\ Weight} * Load\ Factor \tag{1}$$

Assumptions were made about each equipment's model type and manufacturer to obtain their respective peak engine HPs. The manufacturers assumed were CAT, Manitowoc, Nissan, and Miller Welds. The peak engine HP was recorded from the manufacturer specification sheet for each piece of equipment. X-Engineer gives the value for the specific fuel consumption of a diesel engine in grams per kilowatt-hour (g/kWh), however it was converted to pounds per horsepower-hour (lbs/hph) for this calculation. The value for the specific weight of fuel for a diesel engine was provided by Off-Roading Pro, given in pounds per gallon (lbs/gallon). Table 3 displays the estimated fuel consumption in GPH for each piece of equipment.

Table 3: Equipment Fuel Consumption Calculations



Equipment	Manufacturer	Model	Engine	Peak Engine HP	SFC (lbs/HPh)	FSW (lbs/gal)	Load Factor (%)	Fuel Consumption (gallon/hr)
2 pickups	Nissan	Titan XD	Cummins ISV5	310	0.3059	7.5	0.5	**6.32**
Utility Truck & Trailer	Nissan	Titan XD	Cummins ISV5	310	0.3059	7.5	0.5	**6.32**
Dump Truck	CAT	773G	CAT C27	764	0.3059	7.5	0.5	**15.58**
Excavator	CAT	336	CAT C9.3B	311	0.3059	7.5	0.5	**6.34**
Roller/Compactor	CAT	815	CAT C7.1	249	0.3059	7.5	0.5	**5.08**
Backhoe Loader	CAT	450	C4.4 ACERT 106 kW (143 hp) Electronic – Turbo Intercooled	131	0.3059	7.5	0.5	**2.67**
Welder	Miller Welds	Trailblazer 325 Diesel	Kobuta 1800 RPM	24.8	0.3059	7.5	0.5	**0.51**
Loader	CAT	972M	Cat C9.3	299	0.3059	7.5	0.5	**6.10**
Crane	Manitowic	Grove TMS700E	Cummins ISX	450	0.3059	7.5	0.5	**9.18**
Motor Grader	CAT	140 AWD	Cat C9.3	250	0.3059	7.5	0.5	**5.10**
							Light Equipment Avg	4.87
							Heavy Equipment Avg	7.15

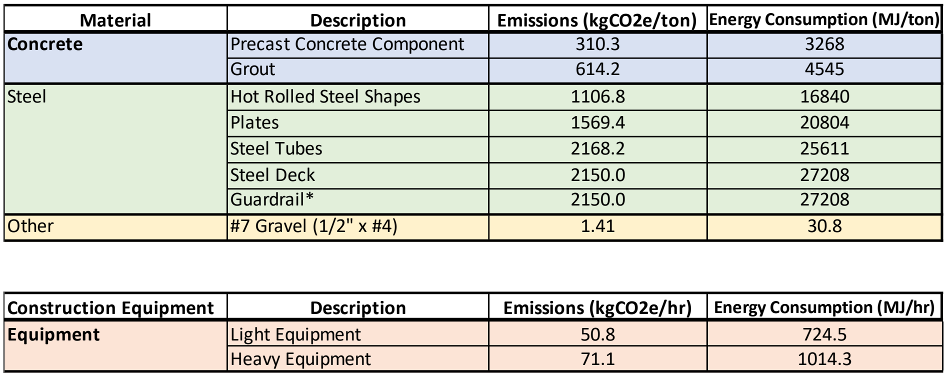
The average fuel consumptions for the light and heavy equipment, calculated in Table 3, are used for the emissions output and energy consumption metrics displayed in Tables 1 and 2. The emissions produced by the construction equipment are based off the emissions output from the diesel fuel burned during the equipment's operation and the upstream emissions for extraction and refining is not considered. The United States Environmental Protection Agency (EPA) provides the amount of emissions in kg CO2e per gallon of diesel fuel burned. This number, multiplied by the fuel consumption rate calculated above, produces the normalized emissions output from the construction equipment in kg of CO2e per hour as reported in Tables 1 and 2.

Energy consumed by the construction equipment is also dependent on the diesel fuel burned while the equipment is in use. The United States Energy Information Administration (EIA) provides the amount of energy output in MJ per gallon of diesel fuel burned. The normalized energy consumption output from the light and heavy construction equipment in MJ per hour is the product of the energy produced per gallon of diesel fuel burned multiplied by the amount of fuel consumed. These results are reported in Tables 1 and 2.

3.3 Summary

Metrics for emissions and energy consumption were determined for the construction, maintenance, and demolition of the two bridges. These values were converted into normalized units so they could be consistently applied to the two bridges as summarized in Table 4. The EPA and AISC average recycling rates were determined for the bridge materials when the bridges are demolished. The material and component weights from the Seltice-Warner and Thornton Depot design drawings and the equipment usage estimated by Whitman County can be used to determine total emissions, energy consumption, and recyclability over the life cycle for each bridge.

Table 4: Emissions and Energy Consumption Metrics Summary



Material	Description	Emissions (kgCO2e/ton)	Energy Consumption (MJ/ton)
Concrete	Precast Concrete Component	310.3	3268
	Grout	614.2	4545
Steel	Hot Rolled Steel Shapes	1106.8	16840
	Plates	1569.4	20804
	Steel Tubes	2168.2	25611
	Steel Deck	2150.0	27208
	Guardrail*	2150.0	27208
Other	#7 Gravel (1/2" x #4)	1.41	30.8

Construction Equipment	Description	Emissions (kgCO2e/hr)	Energy Consumption (MJ/hr)
Equipment	Light Equipment	50.8	724.5
	Heavy Equipment	71.1	1014.3

4 SUSTAINABILITY FOR THE SELTICE-WARNER AND THORNTON DEPOT BRIDGES

The four criteria for the sustainability analysis are emissions, energy consumed, recyclability and waste stream management and life cycle costs. The benchmark CO_2e and energy metrics are applied to the Seltice-Warner and Thornton Depot bridges to determine the total emissions and energy consumed over the life of the structures. The recycled content of both bridges are determined, along with the amount that is discarded to the landfill. Finally, the life cycle costs for each bridge are determined considering the present value cost of the costs associated with construction, maintenance and demolition using an appropriate discount rate.

4.1 Life Cycle Assumptions and Information

The emissions and energy consumption metrics in Tables 1 and 2 are applied to the Seltice-Warner and Thornton Depot bridges by using their component weights and equipment hours. For the construction equipment, the number of hours that the equipment was on site does not necessarily reflect the number of hours the equipment was in active use. Therefore, assumptions were applied, using a usage factor, for a reasonable estimate of emissions and energy consumed during different phases of the life cycle. The equipment was rationally assumed to be used for 30% of the total equipment hours during construction, 100% of the total hours during maintenance, and 50% of the total hours during demolition.

4.2 Adjustment for Difference in Bridge Length

The two bridges are different lengths. To normalize the results, a length factor is applied to length-based quantities for each bridge. The Thornton Depot bridge is 34 ft in length and the Seltice Warner bridge is slightly longer at 35.67 ft. The concrete bridge is taken as the base length, so a factor of 34/35.67 is applied to the applicable length-based Seltice-Warner bridge metrics to adjust for an equivalent 34 ft length. A factor of 1 is applied to non-length-based quantities for the Seltice-Warner bridge and to all components for the Thornton Warner bridge. The two bridges also have slightly different widths. However, the bridges are functionally equivalent for a two-lane roadway. The width difference is due to the component widths of the concrete beams required for the two-lane crossing. Therefore, there is no width adjustment applied to either bridge.

4.3 Greenhouse Gas Emissions and Energy Consumption

To determine the total emissions and energy consumption for the Seltice-Warner steel bridge and the Thornton Depot concrete bridge, the analysis is divided into the sub-totals for the superstructure (prefabricated bridge and additional materials), construction equipment, maintenance equipment and demolition equipment.

4.3.1 Superstructure

Table 5 illustrates the emissions and energy consumption for the Seltice-Warner bridge superstructure and Table 6 shows the same for the Thornton Depot bridge.

The steel bridge superstructure produced a total of 23,554 kg of CO_2e, whereas the concrete bridge produced a total of 34,759 kg of CO_2e. The concrete bridge superstructure produced 47.6% more emissions than the steel bridge superstructure. In terms of energy consumption, the steel bridge superstructure components consumed a total of 328,683 MJ and the concrete bridge superstructure consumed a total of 369,355 MJ. The concrete superstructure consumed 12.4% more energy than the steel superstructure.

Table 5: Seltice-Warner Superstructure Emissions and Energy Consumption

Bridge Component:	Weight (tons):	Emissions (kgCO2e/ton)	Energy (MJ/ton)	Length Factor	Emissions (kgCO2e)	Energy (MJ)
Stringers	9.337	1,106.8	16,840.1	0.953	9,851	149,892
Diaphragm	0.916	1,106.8	16,840.1	1.000	1,013	15,418
Tubes	0.308	2,168.2	25,610.8	0.953	637	7,523
Center Splice Plate	0.152	1,569.4	20,803.6	1.000	239	3,172
Side Dam	0.244	1,569.4	20,803.6	0.953	365	4,838
End Angle	0.274	1,106.8	16,840.1	1.000	304	4,621
Bridge Deck	4.699	2,150.0	27,208.3	0.953	9,631	121,880
Guardrail	0.360	2,150.0	27,208.3	0.953	737	9,328
Bridge Rail Post	0.578	1,106.8	16,840.1	1.000	639	9,725
Post Block	0.096	1,106.8	16,840.1	1.000	107	1,621
Gravel	22.655	1.4	30.8	0.953	30	665
Steel Weight	**16.96**			**Sub-Total Superstructure**	**23,554**	**328,683**
Reinf Concrete Weight	**-**					

Table 6: Thornton Depot Superstructure Emissions and Energy Consumption

Bridge Component:	Weight (tons):	Emissions (kgCO2e/ton)	Energy (MJ/ton)	Length Factor	Emissions (kgCO2e)	Energy (MJ)
Precast Elements	103.840	310.3	3,267.7	1.000	32,217	339,316
Misc. Steel Detail Items	0.338	2,150.0	27,208.3	1.000	727	9,196
Grout	0.999	614.2	4,545.0	1.000	614	4,540
Guardrail	0.360	2,150.0	27,208.3	1.000	773	9,785
Bridge Rail Post	0.387	1,106.8	16,840.1	1.000	428	6,517
Steel Weight	**1.08**			**Sub-Total Superstructure**	**34,759**	**369,355**
Reinf Concrete Weight	**103.84**					

4.3.2 Construction Equipment

Table 7 illustrates the construction equipment emissions and energy consumption for the Seltice-Warner bridge superstructure and Table 8 shows the same for the Thornton Depot bridge.

The equipment used to construct the steel bridge superstructure produced a total of 4,370 kg of CO_2e emissions. The equipment used to construct the concrete bridge superstructure produced 4,768 kg of CO_2e. The concrete bridge produced 9.1% more kg of CO_2e than the steel bridge during construction.

The equipment used to construct the steel superstructure consumed a total of 62,379 MJ and for the concrete superstructure 68,074 MJ. The concrete bridge construction equipment consumed 9.1% more energy than the equipment used for the steel bridge.

Table 7: Seltice-Warner Construction Equipment Emissions and Energy Consumption

Construction Equipment	Hours on Site	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	130	71.1	1,014.3	0.30	2771	39558
Light Equipment	105	50.8	724.5	0.30	1599	22822
				Sub-Total Construction	**4,370**	**62,379**

Table 8: Thornton Depot Construction Equipment Emissions and Energy Consumption

Construction Equipment	Hours on Site	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	128	71.1	1,014.3	0.30	2728	38949
Light Equipment	134	50.8	724.5	0.30	2040	29125
				Sub-Total Construction	**4,768**	**68,074**

4.3.3 Maintenance

Table 9 illustrates the life cycle maintenance emissions and energy consumption for the Seltice-Warner bridge superstructure and Table 10 shows the same for the Thornton Depot bridge.

The emissions totals and energy totals are the same for both bridges. The total emission production for both bridges is 18,270 kg of CO_2e, and the total energy consumed is 260,820 MJ. These values are the same for both bridges because the total maintenance time needed per year for each bridge, the equipment usage factor, and the total number of years of maintenance is assumed to be the same**.**

Table 9: Seltice-Warner Maintenance Equipment Emissions and Energy Consumption

Maintenance	Hours on Site/yr	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	EoL Yrs of Maint	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	3	71.1	1,014.3	1.00	50	10658	152145
Light Equipment	3	50.8	724.5	1.00	50	7613	108675
				Sub-Total Maintenance		**18,270**	**260,820**

Table 10: Thornton Depot Maintenance Equipment Emissions and Energy Consumption

Maintenance	Hours on Site/yr	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	EoL Yrs of Maint	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	3	71.1	1,014.3	1.00	50	10658	152145
Light Equipment	3	50.8	724.5	1.00	50	7613	108675
				Sub-Total Maintenance		**18,270**	**260,820**

4.3.4 Demolition

Table 11 illustrates the demolition emissions and energy consumption for the Seltice-Warner bridge superstructure and Table 12 shows the same for the Thornton Depot bridge.

The equipment used to demolish the steel bridge superstructure produced a total of 1,091 kg of CO_2e emissions. The equipment used to demolish the concrete bridge superstructure produced 1,929 kg of CO_2e. The concrete bridge demolition equipment output 76.8% more kg of CO_2e than the steel bridge equipment. The equipment used to demolish the steel superstructure consumed a total of 15,577 MJ and for the concrete superstructure 27,531 MJ. The concrete bridge demolition equipment consumed 76.7% more energy than the equipment used for the steel bridge.

Table 11: Seltice-Warner Demolition Equipment Emissions and Energy Consumption

Demolition	Hours on Site	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	20	71.1	1,014.3	0.50	711	10143
Light Equipment	15	50.8	724.5	0.50	381	5434
				Sub-Total Yearly Demolition	**1,091**	**15,577**

Table 12: Thornton Depot Demolition Equipment Emissions and Energy Consumption

Demolition	Hours on Site	Emissions (kgCO2e/hr)	Energy (MJ/hr)	Usage Factor	Emissions (kgCO2e)	Energy (MJ)
Heavy Equipment	40	71.1	1,014.3	0.50	1421	20286
Light Equipment	20	50.8	724.5	0.50	508	7245
				Sub-Total Yearly Demolition	**1,929**	**27,531**

4.4 Recyclability and Waste Stream Management

Table 13 displays the tons of steel and concrete either recycled or taken to the landfill for the bridges. The Seltice-Warner bridge is assumed to have 98% of its steel recycled at the end of its life. This equates to 38.83 tons being recycled and 0.79 tons sent to the landfill. The Thornton Depot bridge is assumed to have 82.6% of the concrete and 98% of the steel recycled at the end of its life. The recycled concrete makes up 83.1 tons of the concrete used in the bridge. This leaves 20.8 tons of concrete going to the landfill. There is a little over 1 ton of steel used in the concrete bridge where 1.06 tons will be recycled, and 0.02 tons will be sent to the landfill.

Table 13: Recycling and Disposal Summary

Bridge	Steel Weight (tons)	Concrete Weight (tons)	% of Steel Recycled	%of Concrete Recycled	Tons of Steel Recycled	Tons of Concrete Recycled	Tons of Steel to Landfill	Tons of Concrete to Landfill
Seltice-Warner	39.62	0.00	98%	80%	38.83	0.00	0.79	0.00
Thornton Depot	1.08	103.84	98%	80%	1.06	83.07	0.02	20.77

4.5 Life Cycle Costs

The life cycle costs of the two bridges are broken into two categories: initial costs and the present value of future costs using an appropriate discount rate of 1.7% (Office of Budget and Management). Initial costs include the cost of the prefabricated superstructure and the construction labor, materials, and equipment costs. Future costs include maintenance and demolition costs.

4.5.1 Seltice-Warner

4.5.1.1 Initial Cost

The initial cost of the Seltice-Warner bridge is shown in Table 14. The initial cost considers the prefabricated bridge superstructure, the cost for labor and equipment during the construction of the superstructure, and any additional materials. The length factor is applied to the applicable length-based materials costs, as this bridge is slightly longer than Thornton Depot. Labor and equipment usage would be approximately the same regardless of the small additional length, so the length factor is not applied to those values. The present value initial cost is the same as the initial cost.

Table 14: Seltice-Warner Bridge Initial cost

Bridge Component:	Costs	Length Factor	Adjusted Costs	Present Value Cost
Prefabricated Bridge	$ 60,134.00	0.953	$ 57,323.95	$ 57,323.95
Labor	$ 8,750.00	1.000	$ 8,750.00	$ 8,750.00
Equipment	$ 8,255.00	1.000	$ 8,255.00	$ 8,255.00
Materials	$ 3,491.00	0.953	$ 3,327.87	$ 3,327.87
		Sub-Total Superstructure	**$ 77,656.81**	**$ 77,656.81**

4.5.1.2 Maintenance Costs

The bridge has an assumed life of 75 years. No maintenance is expected to be required for the first 25 years, and it is estimated that $750 per year is expected for labor and equipment the last 50 years of maintenance. These costs are brought to present value cost using the discount rate of 1.7%. First, the cost per year is brought back to the first year of maintenance using the economics *P/A* equation:

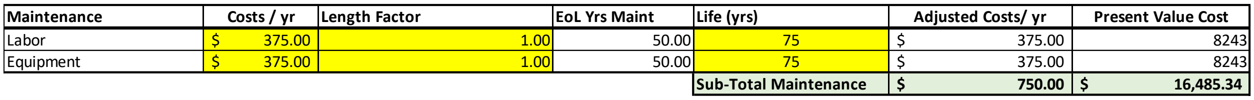
$$P = A\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \tag{2}$$

where i = 0.017 and n = 50. Then, this intermediate value is brought back to the present using the following *P/F* equation:

$$P = F(1+i)^{-n} \tag{3}$$

where n = 25. The present value cost for the Seltice-Warner bridge maintenance is shown in Table 15.

Table 15: Seltice-Warner Bridge Maintenance Costs

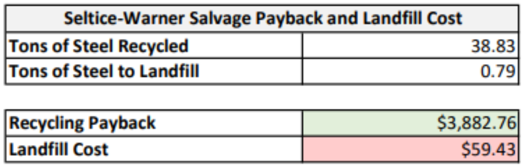


Maintenance	Costs / yr	Length Factor	EoL Yrs Maint	Life (yrs)	Adjusted Costs/ yr	Present Value Cost
Labor	$ 375.00	1.00	50.00	75	$ 375.00	8243
Equipment	$ 375.00	1.00	50.00	75	$ 375.00	8243
				Sub-Total Maintenance	**$ 750.00**	**$ 16,485.34**

4.5.1.3 Demolition Costs

The Pacific Steel Recycling Mill will pay $100/ton for steel scrap. This is a benefit that will decrease the demolition costs for the Seltice-Warner bridge. Alternatively, the Whitman County landfill requires a fee of $75/ton in order to dump waste. Table 16 illustrates the salvage benefit for the recycled steel and the cost for the remaining steel that is sent to the landfill.

Table 16: Seltice-Warner Salvage and Landfill Costs

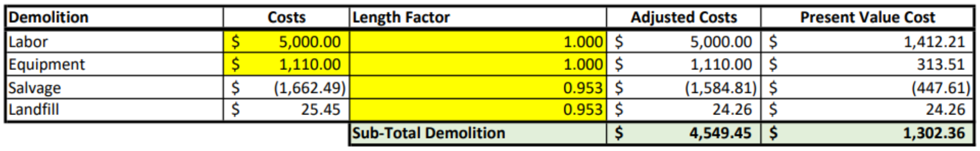


Seltice-Warner Salvage Payback and Landfill Cost	
Tons of Steel Recycled	38.83
Tons of Steel to Landfill	0.79

Recycling Payback	$3,882.76
Landfill Cost	$59.43

The cost of equipment and labor estimated for demolition as well as the salvage cost benefit and disposal costs of the bridge are considered for the total demolition cost as shown in Table 17. Equation 3.0 is used to bring the demolition costs back to a present value with i = 0.017 and n = 50.

Table 17: Steel Bridge Demolition Costs

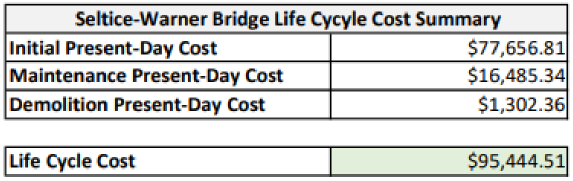


Demolition	Costs	Length Factor	Adjusted Costs	Present Value Cost
Labor	$ 5,000.00	1.000	$ 5,000.00	$ 1,412.21
Equipment	$ 1,110.00	1.000	$ 1,110.00	$ 313.51
Salvage	$ (1,662.49)	0.953	$ (1,584.81)	$ (447.61)
Landfill	$ 25.45	0.953	$ 24.26	$ 24.26
		Sub-Total Demolition	**$ 4,549.45**	**$ 1,302.36**

4.5.1.4 Total Life Cycle Cost

Table 18 presents the present value costs for the construction, maintenance, and demolition phases of the Seltice-Warner bridge. The total life cycle cost is $95,444.

Table 18: Seltice-Warner Total Life Cycle Cost



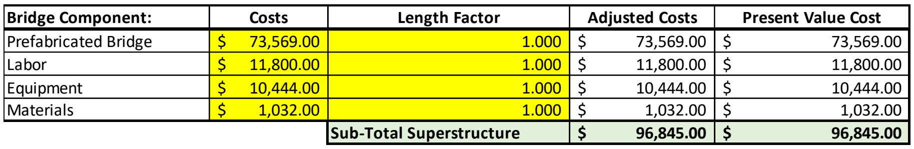
Seltice-Warner Bridge Life Cycycle Cost Summary	
Initial Present-Day Cost	$77,656.81
Maintenance Present-Day Cost	$16,485.34
Demolition Present-Day Cost	$1,302.36
Life Cycle Cost	$95,444.51

4.5.2 Thornton Depot

4.5.2.1 Initial Costs

The initial costs of the Thornton Depot consider the prefabricated bridge superstructure, the cost for labor and equipment during the construction of the superstructure, and any additional materials. The initial cost and present value cost are shown in Table 19.

Table 19: Thornton Depot Bridge Initial Cost

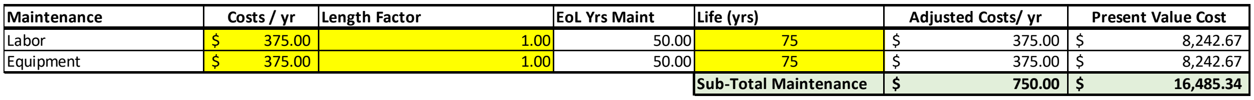


Bridge Component:	Costs	Length Factor	Adjusted Costs	Present Value Cost
Prefabricated Bridge	$ 73,569.00	1.000	$ 73,569.00	$ 73,569.00
Labor	$ 11,800.00	1.000	$ 11,800.00	$ 11,800.00
Equipment	$ 10,444.00	1.000	$ 10,444.00	$ 10,444.00
Materials	$ 1,032.00	1.000	$ 1,032.00	$ 1,032.00
		Sub-Total Superstructure	**$ 96,845.00**	**$ 96,845.00**

4.5.2.2 Maintenance Costs

The bridge has an assumed lifetime of 75 years, in which the first 25 years will be maintenance free and yearly maintenance required for the last 50 years. The cost of maintenance is assumed to be $750/year with $375 for labor and $375 for equipment. Like for the Seltice-Warner bridge, the present value costs were determined using Equations 2.0 and 3.0. The maintenance costs for the Thornton Depot bridge are shown in Table 20.

Table 20: Thornton Depot Bridge Maintenance Costs

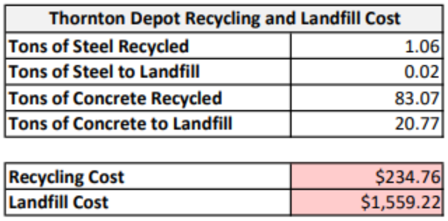


Maintenance	Costs / yr	Length Factor	EoL Yrs Maint	Life (yrs)	Adjusted Costs/ yr	Present Value Cost
Labor	$ 375.00	1.00	50.00	75	$ 375.00	$ 8,242.67
Equipment	$ 375.00	1.00	50.00	75	$ 375.00	$ 8,242.67
				Sub-Total Maintenance	**$ 750.00**	**$ 16,485.34**

4.5.2.3 Demolition Costs

As with the steel bridge, the Pacific Steel Recycling Mill will pay $100/ton for steel scrap. This is a benefit that will decrease the demolition costs for the Thornton Depot bridge. The concrete that will be recycled will be taken to Pro Recycle LLC, however there is a fee of $4.10/ton to recycle concrete. The total cost to recycle the concrete and steel material for the concrete bridge is shown in Table 21. The Whitman County landfill requires a fee of $75/ton in order to dispose of waste.

Table 21: Thornton Depot Salvage and Landfill Costs

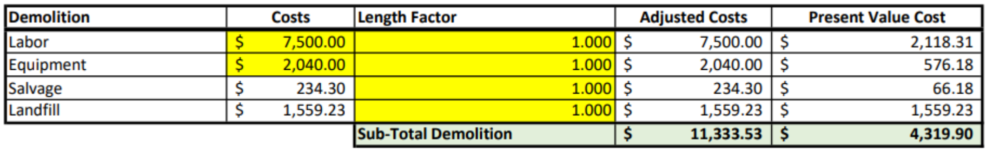


Thornton Depot Recycling and Landfill Cost	
Tons of Steel Recycled	1.06
Tons of Steel to Landfill	0.02
Tons of Concrete Recycled	83.07
Tons of Concrete to Landfill	20.77

Recycling Cost	$234.76
Landfill Cost	$1,559.22

The cost of equipment and labor estimated for demolition as well as the cost to recycle and dispose of the dismantled bridge material are considered in the total demolition cost for the bridge. Again, Equation 3.0 is used to bring the demolition costs back to present value. The adjusted costs and present-day costs for bridge demolition are shown in Table 22.

Table 22: Thornton Depot Bridge Demolition Costs

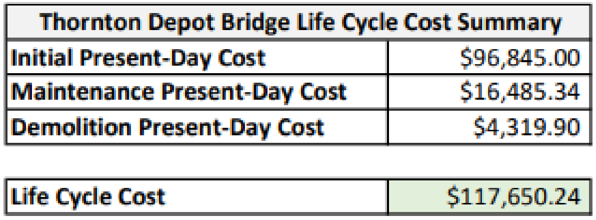


Demolition	Costs	Length Factor	Adjusted Costs	Present Value Cost
Labor	$ 7,500.00	1.000	$ 7,500.00	$ 2,118.31
Equipment	$ 2,040.00	1.000	$ 2,040.00	$ 576.18
Salvage	$ 234.30	1.000	$ 234.30	$ 66.18
Landfill	$ 1,559.23	1.000	$ 1,559.23	$ 1,559.23
		Sub-Total Demolition	**$ 11,333.53**	**$ 4,319.90**

4.5.2.4 Total Life Cycle Cost

Table 23 presents the present value costs for the construction, maintenance, and demolition phases of the Thornton Depot bridge. The total life cycle cost is $117,650.

Table 23: Thornton Depot Total Life Cycle Cost



Thornton Depot Bridge Life Cycle Cost Summary	
Initial Present-Day Cost	$96,845.00
Maintenance Present-Day Cost	$16,485.34
Demolition Present-Day Cost	$4,319.90

Life Cycle Cost	$117,650.24

4.6 Summary

The total emissions for the superstructure components and equipment used during construction, maintenance, and demolition of the Seltice-Warner and Thornton Depot bridges are shown in Table 24. The emissions produced by the Seltice-Warner bridge over its 75-year lifetime totaled to 47,284 kg of CO_2e. This is equivalent to the emissions produced by 10.3 passenger cars driven over the course of one year or 118,834 miles driven by an average passenger car (Greenhouse Gas Equivalencies Calculator, EPA). The emissions produced by the Thornton Depot bridge over its 75-year lifetime totaled to 59,726 kg of CO_2e. This is equivalent to the emissions produced by 13 passenger cars driven over the course of one year or 150,103 miles driven by an average passenger car. The concrete bridge will produce 26.3% more CO_2e emissions (2.3 passenger car years or 31269 miles) over its lifetime than the steel bridge.

Table 24: Emissions

Emissions (kgCO2e)					
	Superstructure	**Construction**	**Maintenance**	**Demolition**	**Total**
Steel	23554	4370	18270	1091	47284
Concrete	34759	4768	18270	1929	59726

The total energy consumption for the superstructure components and equipment used during construction, maintenance, and demolition are shown in Table 25. The energy consumed by the Seltice-Warner bridge over its lifetime totaled to 667,459 MJ. This is equivalent to the energy use of 6.5 private residence homes in one year (Greenhouse Gas Equivalencies Calculator, Natural Resources Canada). The energy consumed by the Thornton Depot bridge over its lifetime totaled to 725,780 MJ. This is equivalent to 7.1 homes' energy use for a year. The concrete bridge will have consumed 8.7% more energy (0.6 home years) than the steel bridge over their equivalent 75-year lifespans.

Table 25: Energy Consumption

Energy (MJ)					
	Superstructure	**Construction**	**Maintenance**	**Demolition**	**Total**
Steel	328683	62379	260820	15577	667459
Concrete	369355	68074	260820	27531	725780

The total life cycle cost of each bridge is the sum of the present value initial, maintenance, and demolition costs. Table 26 displays the present value costs and the life cycle costs. The life cycle cost for the Seltice-Warner bridge over its 75-year lifespan is $95,445. The life cycle cost of the Thornton Depot bridge over an equivalent lifespan is $117,650. The Seltice-Warner bridge has $22,205 less life cycle cost.

Table 26: Life cycle Cost

Life Cycle Cost					
	Superstructure	**Tot Initial**	**PV Maint**	**PV Demo**	**Total LCC**
Steel	$ 57,324	$ 77,657	$ 16,485	$ 1,302	$ 95,445
Concrete	$ 73,569	$ 96,845	$ 16,485	$ 4,320	$ 117,650

5 DECISION-MAKING ANALYSIS CONSIDERING SUSTAINABILITY

The owner of the bridge, a county or a state, selects which type of bridge to build based on selection criteria. Historically, the decision has been based on first or initial costs of installing the bridge. Responsible owners are beginning to consider life cycle costs for bridge selection decisions. The sustainability benefits of reduced emissions, energy consumption and landfill usage has not typically been recognized in decision criteria.

Sustainable design is grounded on the concept that society is willing to pay extra for reducing harmful effects on the environment. To consider sustainability in the selection of the optimal bridge type, a multi-criteria decision-making analysis (MCDA) can be employed to develop a benefit-cost ratio that explores the additional sustainability benefits secured with respect to cost.

An MCDA is applied to the Seltice-Warner steel and Thornton Depot concrete bridges to examine the sustainability characteristics of the two bridges. Following the MCDA, a simple decision-making procedure is developed so that owners can consider sustainability in the bridge selection process.

5.1 Sustainability Multi-Criteria Decision-Making using Benefit/Cost Analysis

A multi-criteria decision-making analysis (MCDA) using benefit-cost analysis was performed by normalizing and weighting the emissions, energy consumption and recyclability and waste stream management characteristics using simple utility functions and comparing them to normalized life cycle costs. The benefit-cost analysis shows how much benefit (in this case sustainability benefit) is obtained for extra money spent than the alternative options.

5.1.1 Utility Functions

The utility function produces a normalized benefit where the larger the number, the higher the benefit (the lower the emissions or energy consumed). A simple linear utility function was applied for each bridge, where the value of the best alternative is 1.0 and the other is a percentage of that best. The normalized emissions benefit for the Seltice-Warner bridge is

$$\frac{47{,}284\ CO_2e}{47{,}284\ CO_2e} = 1.0$$

and for the Thornton Depot bridge

$$\frac{47{,}284\ CO_2e}{59{,}726\ CO_2e} = 0.792$$

The same process is applied for the energy consumed normalized benefit. Tables 27 and 28 present the emissions and energy consumption utility function benefit values.

Table 27: Emissions Normalized Benefit and Scores

Emissions		
Bridge	**Emissions (kgCO2e)**	**Normalized Benefit**
Steel	47284	1.000
Concrete	59726	0.792

Table 28: Energy Consumption Normalized Benefit and Scores

Energy Consumption		
Bridge	**Energy Consumed (MJ)**	**Normalized Benefit**
Steel	667459	1.000
Concrete	725780	0.920

The recyclability and landfill utility function is slightly different, as it is realistic to say that a bridge could be 100% recycled or 100% of it disposed to the landfill. The normalized benefit scores for the recyclability and waste stream management criteria are based on the percent recycled by weight as shown in Table 29. A score of zero would be assigned for no (0%) recycling and a score of 1.0 for completely (100%) recycled.

Table 29: Recyclability Normalized Benefit and Scores

Recyclability & Landfill		
Bridge	**% Recycled**	**Normalized Benefit**
Steel	98.00%	0.980
Concrete	80.19%	0.802

The life cycle costs were also normalized by a simple linear utility function (lower is better) where the lower the life cycle cost, the lower the utility function. The value of the highest life cycle cost is 1.00 and the other is a percentage of the highest life cycle cost bridge. Table 30 presents the life cycle utility function costs.

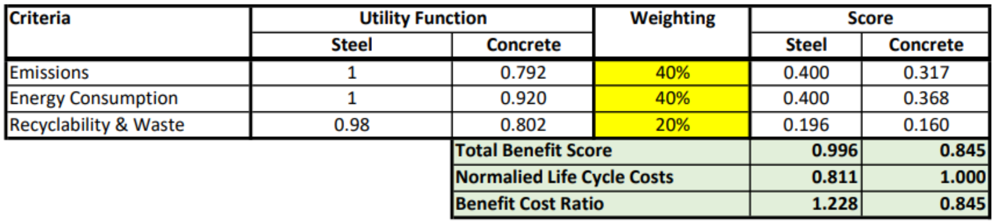
Table 30: Life Cycle Costs Normalized Costs

Life Cycle Costs		
Bridge	**Life Cycle Cost**	**Normalized Cost**
Steel	$ 95,444.51	0.811
Concrete	$ 117,650.24	1.000

5.1.2 Weighting of Benefit Criteria

The normalized benefit criteria are weighted according to the importance of the criteria. The owner or society would decide the importance of each of the benefit criteria. For this study, a weighting of 40% were assigned to each of emissions and energy consumption and 20% to recyclability and waste stream management criterion. The weights are multiplied by the respective normalized benefit scores, then added up to determine a total benefit score for each bridge. The weights and final benefit scores are shown in Table 31. The higher the score, the better performance in terms of sustainability.

Table 31: Multi-Criteria Benefit-Cost Analysis



Criteria	Utility Function		Weighting	Score	
	Steel	Concrete		Steel	Concrete
Emissions	1	0.792	40%	0.400	0.317
Energy Consumption	1	0.920	40%	0.400	0.368
Recyclability & Waste	0.98	0.802	20%	0.196	0.160
		Total Benefit Score		**0.996**	**0.845**
		Normalied Life Cycle Costs		**0.811**	**1.000**
		Benefit Cost Ratio		**1.228**	**0.845**

5.2 Decision Making

When owners decide on which bridge to build, they have a choice in the decision-making process. They may base the decision on (1) the fabricated bridge cost from the manufacturer, (2) the initial cost for installing the bridge which includes labor, equipment, and additional materials, (3) life cycle costs considering all future costs, or (4) consideration of sustainability benefits and costs possibly using benefit-cost ratios. For this study, the benefit-cost ratios are based on life cycle sustainability and life cycle costs. However, the benefit-cost ratio could be applied to any phase of the bridge service, i.e., considering sustainability only for the installation of the bridge.

Using the respective sustainability benefit and cost scores, a benefit-cost analysis is performed to determine if the steel or concrete bridge has the most sustainability benefit with respect to the costs. For the steel bridge, the benefit-cost ratio is 1.233 and for the concrete bridge it is 0.845 as shown in Table 31. The steel bridge has both a higher benefit and lower cost, so it is clearly the best option for this analysis. The decision of which bridge to build is trivial for these two bridges.

When the decision is not trivial, for instance if the steel bridge had higher life cycle costs, to consider sustainability in the decision of which bridge should be built, the question to answer is, "what additional cost would society or the owner be willing to pay to increase sustainability benefits?" Examples of sustainability benefits would include reduced CO_2e emissions, reduced energy consumption or higher rates of recyclability (less material going into the landfill).

To develop procedures so that society or the owner can consider sustainability when the decision is not trivial, this study considers two "what if" scenarios applied to the two bridges. The first is the sensitivity of the prefabricated steel bridge cost as it relates to initial cost, life cycle cost and sustainability benefit-cost ratio decision making. The second assumes the concrete bridge has a lower initial cost than the steel bridge and develops a procedure to consider the sustainability benefits gained with the additional cost of the steel bridge.

5.3 Sensitivity Based on Seltice-Warner Prefabricated Bridge Costs

The Seltice-Warner bridge has reduced emissions, reduced energy consumption and less material disposed in the landfill compared to the Thornton Depot bridge. The initial and life cycle costs for the steel bridge are also less than that for the concrete bridge, but what if the steel bridge had higher costs? There are sustainability benefits for the steel bridge and the question is "what additional costs are acceptable for these sustainability benefit gains?" To examine this question, a sensitivity analysis was performed to determine how much the prefabricated Seltice-

Warner bridge would have had to cost for the Thornton Depot bridge to outperform it in each of the categories of prefabricated bridge cost, initial cost, life cycle cost, and sustainability benefit/cost ratio. The results are shown in Table 32. The decision-making options of prefabricated bridge costs, initial bridge costs, life cycle costs, or sustainability benefit-cost ratios and the best option (either steel or concrete) are shown in Table 33 for the sensitivity analysis.

Table 32: Sensitivity Analysis Based on Seltice-Warner Prefabricated Bridge Costs

Bridge Material	Criteria	Additional Prefabricated Steel Bridge Cost				
		Case 1	Case 2	Case 3	Case 4	Case 5
		$0	$20,000	$23,000	$26,000	$46,000
Steel	PreFab Bridge Cost	$60,134	$80,134	$83,134	$86,134	$106,134
	Initial Cost	$77,657	$96,722	$99,582	$102,442	$121,507
	Life Cycle Cost	$95,445	$114,510	$117,370	$120,230	$139,295
	Sustainability Benefit/Cost	1.228	1.023	0.998	0.996	0.996
Concrete	PreFab Bridge	$73,569	$73,569	$73,569	$73,569	$73,569
	Initial Cost	$96,845	$96,845	$96,845	$96,845	$96,845
	Life Cycle Cost	$117,650	$117,650	$117,650	$117,650	$117,650
	Sustainability Benefit/Cost	0.845	0.845	0.845	0.863	1.000

Table 33: Results of Sensitivity Analysis

Decision Criteria	Additional Prefabricated Steel Bridge Cost				
	Case 1	Case 2	Case 3	Case 4	Case 5
	$0	$20,000	$23,000	$26,000	$46,000
PreFab Bridge Cost	Steel	Concrete	Concrete	Concrete	Concrete
Initial Cost	Steel	Steel	Concrete	Concrete	Concrete
Life Cycle Cost	Steel	Steel	Steel	Concrete	Concrete
Sustainability Benefit/Cost	Steel	Steel	Steel	Steel	Concrete

Case 1 in Table 32 is the actual Seltice-Warner costs where the prefabricated bridge cost is $60,134. The result is that the decision is trivial since the steel bridge has better sustainability benefits and lower costs than the Thornton Depot bridge for all categories in Table 33.

For Case 2, where $20,000 was added to the steel prefabricated bridge cost, the concrete bridge would have a lower prefabricated bridge cost (Table 32), but the steel bridge has lower initial and life cycle costs and a higher sustainability benefit-cost ratio. Even though the prefabricated steel bridge has a higher cost, it should be the better choice based on sustainability and initial and life cycle costs.

In Case 3, adding $23,000 to the cost of the prefabricated steel bridge results in the concrete bridge having a lower prefabricated bridge cost and a lower initial cost. This is the historical decision criteria where the owner selects a bridge based on “first costs” as shown in Table 33. However, because of lower demolition costs, the steel bridge still has lower life cycle costs.

Case 4 is where consideration of life cycle costs are incorporated. If the prefabricated steel bridge cost increases $26,000, the concrete bridge also has lower life cycle costs. Responsible owners are beginning to consider life cycle costs in bridge decisions. Yet, the sustainability benefits of reduced emissions, energy consumption and landfill usage for the steel bridge are not recognized in the decision criteria. Considering the sustainability benefits through the benefit-cost analysis performed herein, the steel bridge has a higher benefit-cost ratio and should be selected.

Case 5 is where the concrete bridge outperforms the steel bridge in all four criteria. If the prefabricated steel bridge costs an additional $46,000, not only does the concrete bridge have a lower prefabricated bridge cost, initial cost, and life cycle cost, but it also has a higher sustainability benefit-cost ratio. According to the utility functions and weighted multi-criteria decision-making analysis employed in this study; the sustainability benefits of the steel bridge are not worth the extra costs of the prefabricated steel bridge.

The results of this analysis lead to a procedure that can be developed that allows society or the owner to consider sustainability benefits based on acceptable costs for reducing emissions, energy consumption and landfill use.

5.4 Considering Sustainability Benefits Based on Prefabricated Bridge Costs

The idea of considering sustainability in the design of a bridge entails answering the question, “what additional cost would society or the owner be willing to pay to increase sustainability benefits?” The Seltice-Warner bridge reduces emissions 12,442 kg of CO_2e and reduces energy consumption 58,321 MJ compared to the Thornton Depot bridge. The Seltice-Warner bridge also sends 20 tons less material to the landfill than the Thornton Depot bridge.

A decision-making process is developed based on the costs of the prefabricated bridge costs. The assumptions are shown in Table 34 where the concrete bridge has fixed prefabricated bridge, initial and life cycle costs and the steel bridge has an additional $X prefabricated bridge cost, which would translate to additional $X initial and life cycle costs. For the Seltice-Warner and Thornton Depot bridge comparison, $X would represent the additional prefabricated steel bridge cost with all other costs not changing.

Table 34: Assumptions for Bridge Costs

Phase	Steel	Concrete
Prefabricated Bridge Cost	$40000+X	$40,000
Initial Costs	$50000+X	$50,000
Life Cycle Costs	$100000+X	$100,000

If steel bridge cost is an additional $X, the cost for reducing emissions and energy consumption would be $X/12442 kg CO_2e and $X/58321 MJ, respectively. Figure 6 illustrates the cost for emission reduction and Figure 7 shows the costs for energy consumption reduction for the additional cost of the steel bridge. To put this into perspective, if the steel bridge cost an additional $1,000, the cost to reduce the emissions is $0.08/kg CO_2e (12.4 kg CO_2e for every extra $ spent). However, the cost of reduction becomes less efficient for increasing additional cost. If the steel bridge cost an additional $8,000, the cost to reduce emissions is $0.64/kg CO_2e (1.56 kg CO_2e for every additional $ spent).

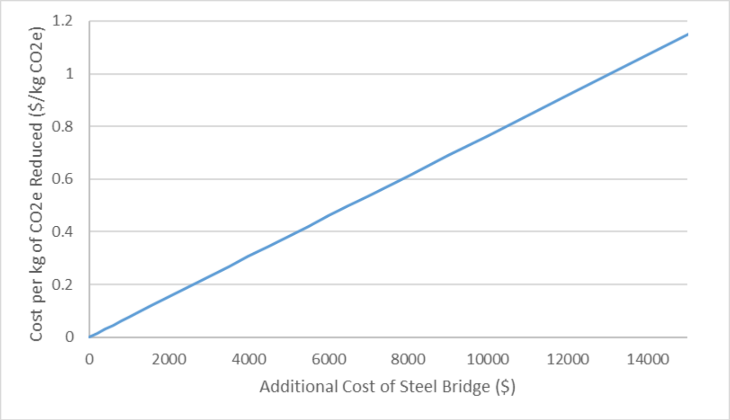


Figure 6: Cost of CO2e Reduction per Additional Dollar Spent

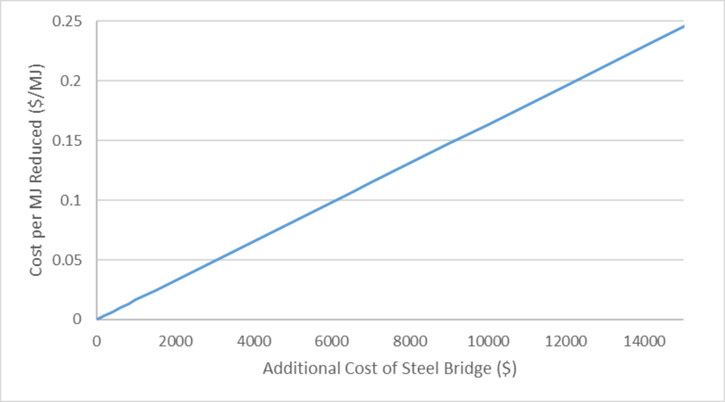


Figure 7: Cost of Energy Reduction per Additional Dollar Spent

To consider sustainability when selecting a bridge, if society or the owner determines an acceptable cost for reducing emissions and energy consumption, the equivalent cost can be considered in the decision-making process. For instance, if society or the owner is willing to pay $1 for every 5 kg of CO2e reduced ($0.20/kg CO2e) and $1 for every 25 MJ of energy reduced ($0.04/MJ), then the owner can consider an equivalent cost of $0.20x12,442 = $2,488.40 for reducing emissions and $0.04x58,321 = $2,332.84 for reducing energy consumption as a benefit to the steel bridge.

A similar method can be applied to the landfill use. If society or the owner is willing to pay $50 as a societal benefit for every ton ($50/ton) not sent to the landfill, then the owner can consider an equivalent cost of $50*20 = $1,000 for reducing landfill use as a benefit to the steel bridge.

The benefit to the steel bridge, a total of $5,821, can be subtracted from the steel bridge costs, $40,000+$X - $5,821, and compared to the cost of the concrete bridge of $40,000. For this comparison, the steel bridge could cost $5,821 more than the concrete for the two bridges to be equivalent. If the additional $X cost of the steel bridge is less than $5,821, the steel bridge should be selected. If the additional $X cost of the steel bridge is more than $5,821, then the concrete bridge should be selected.

5.5 Decision Making Procedure Considering Sustainability

This process can be extended for consideration of any number of alternatives (bids) with differing initial costs or life cycle costs for a bridge project. An Equivalent Cost, that considers sustainability benefits, can be determined for each alternative and compared for lowest Equivalent Cost:

Equivalent Cost = [Initial or Life Cycle Cost]
– [Reduced kg CO2e from Max CO2e]*(Accepted $/kg CO2e)
– [Reduced MJ form Max MJ]*(Accepted $/MJ)
– [Reduced Landfill tons from Max Landfill tons]*(Accepted $/ton) (4)

Table 35 demonstrates the procedure for five alternatives with differing initial costs and emissions, energy consumption and landfill use. The analysis can be used for initial costs and initial sustainability characteristics or life cycle costs and life cycle sustainability characteristics as preferred by the owner. If the accepted sustainability costs are $0.20/kg CO2e for emissions, $0.04/MJ for energy consumption and $50/ton for landfill use, the Equivalent Costs can be compared to select the optimal bridge.

Table 35: Equivalent Cost Comparison Considering Sustainability

Bridge	Initial or	Initial or Life Cycle Total				Reduction			Cost Benefit		Equivalent Cost
	Life Cycle Cost	kg CO2e	MJ Consumed	Landfill (tons)	kg CO2e	MJ Consumed	Landfill (tons)	kg CO2e	MJ Consumed	Landfill (tons)	
Alt 1	$ 100,000	59726	725780	21	10274	24220	0	$2,055	$969	$0	$96,976
Alt 2	$ 105,000	70000	720000	10	0	30000	11	$0	$1,200	$540	$103,261
Alt 3	$ 105,000	47284	667459	1	22716	82541	20	$4,543	$3,302	$1,000	$96,155
Alt 4	$ 107,000	45000	664000	10	25000	86000	11	$5,000	$3,440	$540	$98,021
Alt 5	$ 107,000	44000	750000	1	26000	0	20	$5,200	$0	$1,000	$100,800
	Max	70000	750000	21							

Alternative 1 has the lowest initial (or life cycle) cost and would be selected based on a lowest first (or life cycle) cost criterion. However, Alternative 1 does not have as much monetary sustainability cost benefits with the societal accepted costs for emissions, energy consumption and landfill use as other alternatives. Alternative 4 has the highest sustainability cost benefits, but it also has a high initial cost and the sustainability cost benefits do not overcome the higher initial cost compared to other alternatives. Alternative 3 has the lowest Equivalent Cost and should be selected based on the sustainability cost benefits overcoming a higher initial cost.

The least costly is Alternative 1 at $100,000 that has sustainability benefits worth $3,024 to society for an Equivalent Cost of $96,976. Alternative 3 costs $5,000 more at $105,000, but it also returns $8,845 worth of sustainability benefits for an Equivalent Cost of $96,155. Considering sustainability in bridge selection criteria, Alternative 3 should be chosen over Alternative 1 even though it is more expensive. The initial cost of Alternative 3 is $5,000 more than Alternative 1, but the societal sustainability benefit of Alternative 3 is $5,821 over that of

Alternative 1. According to society's acceptable costs for reducing emissions, energy consumption and landfill use, although Alternative 3 costs more than Alternative 1, society is reaping an acceptable $8,845 return on the $5,000 extra cost investment for Alternative 3.

This procedure is the same as an incremental benefit-cost analysis. Incremental benefit-cost analysis uses the least expensive alternative and determines the incremental benefits and the incremental costs of more expensive alternatives. If the more expensive alternative returns more benefits than the additional cost, the incremental benefit-cost ratio is greater than 1.0 and the more expensive alternative should be selected. However, owners are not familiar with incremental benefit-cost analysis and the Equivalent Cost procedure developed here is directly comparable to historical first cost comparisons or life cycle cost comparisons and would be better understood by owners.

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6 SUMMARY AND CONCLUSIONS

The life cycle sustainability of steel and concrete short simple span rural bridges was examined by comparing two nearly identical, functionally equivalent steel and concrete bridges. The Seltice-Warner steel bridge is a prefabricated rolled-beam modular bridge, and the Thornton Depot concrete bridge is a prefabricated precast prestressed girder bridge. Both bridges were built by the Whitman County, Washington bridge crew. A multi criteria decision making analysis (MCDA) using a cost benefit analysis was employed with criteria and benchmarks developed from existing sustainability rating systems for buildings (LEED) and infrastructure (Envision). Four criteria were considered for only the superstructures of the two bridges for a direct steel and concrete bridge comparison: total emissions (kg of CO2e); total energy consumption (MJ); end of life recyclability and waste stream management (percent weight recycled); and life cycle costs (present value costs). Drawings for the bridges and information on construction and estimates for maintenance and demolition equipment usage and labor was obtained from Whitman County personnel.

The benchmarks for the criteria included emissions, energy consumption, recyclability and waste stream management and costs for the bridge materials, construction, maintenance and demolition phases over the bridge life cycle. For fabricated material and construction equipment sustainability metrics, Environmental Product Declarations (EPD) that best fit the material and components for emissions and energy consumption were used in the analysis. Sustainability metrics for construction equipment were developed from appropriate sources.

The results show that, over the life cycle, the Thornton Depot concrete bridge (1) results in 26.3% more embodied CO2e emissions, (2) consumes 8.7% more energy, and (3) recycles 17.8% less material (assuming the concrete is recycled) at the end of the bridge life than the Seltice-Warner steel bridge. The Thornton Depot bridge also has a life cycle cost 23% higher than the Seltice-Warner bridge.

The MCDA used simple utility functions to normalize the emissions, energy consumption and recyclability and waste stream management sustainability totals into sustainability benefits. The life cycle costs were also normalized by a simple utility function. The results show that, for these two bridge examples, the Seltice-Warner steel bridge outperforms the Thornton Depot concrete bridge in emissions, energy consumption, and recyclability and waste stream management sustainability benefits. Applying an importance weighting scheme of 40% for emissions, 40% for energy consumption and 20% for recyclability and waste stream management results in a total sustainability benefit (higher is better) score. The benefit score for the Seltice-Warner steel bridge is 0.996 and it is 0.845 for the Thornton-Depot concrete bridge. The steel bridge also had lower life cycle costs. The normalized cost (lower is better) for Seltice-Warner was 0.808 and it was 1.00 for Thornton-Depot. The benefit score is divided by the normalized life cycle cost to determine a benefit-cost ratio considering sustainability. The benefit cost ratio for the steel bridge is 1.226 where it is 0.845 for the concrete bridge.

The historical decision criteria for choosing which bridge should be built is based on first costs for installing the bridge. Responsible owners may also consider life cycle costs over the bridge service life. Neither of these consider sustainability benefits of one bridge over another. Sustainable design is predicated on the idea that society is willing to pay extra for reducing harmful effects on the environment. For sustainability considerations, the purpose of an MCDA is to decide which bridge the owner should choose considering the weighted sustainability benefits related to the costs. Considering sustainability in the design of a bridge entails answering the question, “what additional cost would society or the owner be willing to pay to increase sustainability benefits?” Examples of sustainability benefits would include reduced CO_2e emissions, reduced energy consumption or higher rates of recyclability.

For the Seltice-Warner and the Thornton Depot bridges, the steel bridge outperforms the concrete bridge for initial costs, life cycle costs and sustainability benefits, so the decision is straightforward and trivial. However, the report develops procedures so that society or the owner can consider sustainability when the decision is not trivial.

The report considers two “what if” scenarios applied to the two bridges. The first is the sensitivity of the prefabricated steel bridge cost as it relates to initial cost, life cycle cost and the MCDA sustainability benefit-cost ratio decision process. The results show that the Seltice-Warner steel bridge cost could increase significantly, above the initial and life cycle costs of the Thornton Depot concrete bridge, and still have a preferable benefit-cost ratio due to the sustainability benefits of the steel bridge according to the weighted criteria of the multi-criteria decision-making analysis.

The second scenario assumes the concrete bridge has the same initial cost as the steel bridge and examines the sustainability benefits gained with an increasing cost of the steel bridge. The procedure is framed as reductions in CO_2e emissions or reduction in energy consumed for every extra dollar spent. The results show that the efficiency of the sustainability benefits gained decreases as the additional cost of the steel bridge increases. However, the scenario sets up a decision-making concept, similar to building sustainability practice and along the line of an incremental benefit-cost ratio, of the additional costs associated with reducing emissions or energy consumption.

This concept is extended to a simple decision-making procedure that considers monetized sustainability benefits for any number of bridge alternatives associated with a bridge project. The owner or society determines the acceptable additional costs they are willing to pay for reducing emissions, reducing energy consumption, or reducing material sent to the landfill. The initial cost, or life cycle cost, is adjusted for the monetary sustainability benefits associated with reducing harmful environmental impacts to determine an equivalent cost that can be compared among alternatives to select the best alternative. The alternative bridge that is built can be decided based on the initial costs, or life cycle costs, and consideration of acceptable additional costs that gains desirable sustainability benefits.

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