

Development of Cost-Competitive Timber Bridge Designs for Long- Term Performance

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Natural Resources Research Institute
University of Minnesota Duluth

June 2020

Research Project
Final Report 2020-16



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Technical Report Documentation Page

1. Report No. MN 2020-16	2.	3. Recipients Accession No.	
4. Title and Subtitle Development of Cost-Competitive Timber Bridge Designs for Long-Term Performance		5. Report Date June 2020	
		6.	
7. Author(s) Brian Brashaw, James Wacker, Don Fosnacht, Matt Aro, Matthew Young, Robert Vatalaro		8. Performing Organization Report No.	
9. Performing Organization Name and Address Natural Resources Research Institute University of Minnesota Duluth 5013 Miller Trunk Highway Duluth, MN		10. Project/Task/Work Unit No. CTS#2018022	
		11. Contract (C) or Grant (G) No. (C) 99008 (WO) 227	
12. Sponsoring Organization Name and Address Local Road Research Board Minnesota Department of Transportation Office of Research & Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes http://mndot.gov/research/reports/2020/202016.pdf http://mndot.gov/research/reports/2020/202016A.pdf			
16. Abstract (Limit: 250 words) Modern timber bridges have shown that timber is a durable option for primary structural members in highway bridges and can perform satisfactorily for 50 years or longer when properly designed, fabricated and maintained. However, various cost assumptions have indicated that timber bridges are more expensive than concrete bridges. This project was undertaken to better understand the benefits and costs of using timber bridges as a viable substitute for other bridge construction materials and designs. Two demonstration construction projects were completed to develop comparative information. A steel girder with a transverse glulam deck bridge with a curbless, crash-tested railing system was built, and a spike-laminated longitudinal deck bridge was constructed. Both projects were completed and allowed for a good comparison to be developed both in terms of project-specific cost and the time required for bridge construction completion. These projects showed that the main advantage of a timber bridge is the speed of superstructure construction with the other costs similar to that of other materials. It is clear from previous case studies, interviews with engineers, contractors, and suppliers, and the projects that timber superstructures can be installed within days to weeks, compared to months for other materials.			
17. Document Analysis/Descriptors Wooden bridges, Highway bridges, Timber, Timber construction		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 214	22. Price

DEVELOPMENT OF COST-COMPETITIVE TIMBER BRIDGE DESIGNS FOR LONG-TERM PERFORMANCE

FINAL REPORT

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June 2020

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

This report represents the results of research conducted by the authors and does not necessarily represent the views or policies of the Minnesota Department of Transportation or the University of Minnesota Duluth and its subcontractors including the USDA Forest Service. This report does not contain a standard or specified technique.

The authors, the Minnesota Department of Transportation, and the University of Minnesota Duluth and its subcontractors including the USDA Forest Service do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

ACKNOWLEDGMENTS

The financial and logistical support provided by the Local Road Research Board of the Minnesota Department of Transportation is appreciated for this project. The authors acknowledge the excellent research team from the University of Minnesota Duluth's Natural Resources Research Institute and their research partners from USDA's Forest Service, Laminated Concepts Inc., Iowa State University, and LHB Engineering. The valuable engagement of various timber bridge manufacturers is also appreciated, notably Wheeler Consolidated and Alamco Wood Products, a division of Bell Lumber and Pole Company. Thank you to the engineering staffs from St. Louis County and Hennepin County who facilitated the completion of the design and construction of the two demonstration bridges during this project.

The support and engagement from the Minnesota Department of Transportation Bridge office facilitated this project and is recognized. Furthermore, thanks are extended to the Technical Advisory Panel (TAP), which provided meaningful review and engagement throughout the project.

The project team, cooperators, and TAP included the following members:

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LIST OF ABBREVIATIONS

AASHTO - American Association of State Highway and Transportation Officials

ft – feet

Glulam - Glued-laminated timber

in - inches

km - kilometers

lb. – pounds

LCCA – life-cycle cost analysis

LCA – life-cycle assessment

LRFD – load and resistance factor design

MnDOT – Minnesota Department of Transportation

NBI - National Bridge Inventory

NCHRP - National Cooperative Highway Research Program

EXECUTIVE SUMMARY

Minnesota Department of Transportation (MnDOT) data shows that only 25 timber beam or slab bridges were constructed in Minnesota from 2000 through 2019. During the same period, over 620 concrete slab spans or prestressed concrete beam bridges were constructed. This occurred due to several factors, including misconceptions about the durability, structural adequacy and expense of constructing timber bridges. However, significant advancements in design, preservation, maintenance and inspection of modern timber bridges have been made. Recent national service-life assessment research has shown that timber is a durable option for primary structural members in highway bridges and can perform satisfactorily for 50 years or longer when properly designed, fabricated and maintained. However, both anecdotal assumptions and cost reports have indicated that timber bridges are more expensive than concrete bridges to construct (MnDOT, 2020).

In this project, information was gained through project activities informed by literature reviews, surveys of county engineers, and demonstration construction projects, with a goal of seeing an increase in the construction of cost-competitive timber-based bridges in Minnesota. To improve awareness of modern timber bridges for state and local bridge owners, design aids were developed for three bridge superstructure types: 1) steel stringers with a transverse glulam deck, 2) glulam stringer with a transverse glulam deck, and 3) spike-laminated longitudinal deck. These aids generally include the following information for each superstructure type: perspective drawing and photographic view, design information, connection detail, crash-tested bridge railing options, and flashing detail options.

Other options for improving cost-effectiveness of timber bridges include preservative selection, contracting and construction options, bridge design, fabrication, construction/installation, and design innovations to minimize long-term maintenance. Specifically, this includes the potential for streamlined MnDOT preservative approvals, winter construction, inclusion of timber designs into bid specifications to increase competition, expanded use of American Association of State Highway Transportation Officials-Load and Resistance Factor Design (AASHTO-LRFD) multiple presence factors, contractor supplied pre-letting designs, alternate designs for abutments, and other activities underway by bridge designers, engineers and suppliers.

Research and demonstration projects clearly show that the main advantage of a timber bridge is the speed of superstructure construction. It is clear from previous case studies, interviews with bridge engineers, owners, contractors, and suppliers, and demonstration projects that timber superstructures can be installed within days to weeks, as compared to months for other materials.

Two demonstration construction projects were completed. In the first project, a St. Louis County construction crew installed a steel girder with a transverse glulam deck bridge with a curbless crash-tested railing system. The bridge installation was efficient and new flashing designs were used to direct water off the bridge deck. Despite several challenging site conditions, the project was successfully installed. While the overall project costs were significant, costs for the wood-based materials and labor were similar to those for other alternative designs. In the second project, Hennepin County contracted

with a Minnesota construction firm. The previous bridge was removed in December, piles installed in January, and the timber superstructure constructed in March. However, spring rains created a long delay in other roadway work and paving, resulting in an opening delay until July. However, the timber superstructure was completed in approximately five days. The feedback from the county (design engineer, construction engineer, and construction inspector) was all positive about the timber aspects of the project. This project also was completed at a very difficult site, making a direct cost comparison to alternative designs complicated. However, it appears this project was cost-competitive based on the information collected. In the demonstration projects, life-cycle assessments (LCA) were completed for each of the two demonstration projects. The analysis was only conducted on the actual design and construction materials used in the timber-based projects. Ideally, it would have been undertaken in comparison to other bridge materials, but that was outside the scope of the project. However, the alternate concrete designs for each project could be assessed in the future and compared. Regardless, this effort created a baseline process and examples for future LCA.

Minnesota has two timber bridge component suppliers, Wheeler Lumber, LLC and Bell Structural Systems. These companies have significant experience in working with county engineers to support the design and construction of timber bridges that are cost-effective and longlasting. Further, there are other companies in the US with experience in the design, specification, and construction of timber bridge systems. It was shown that there are a number of consultant and construction firms in Minnesota that have experience in design and construction of timber bridges. At least one county (St. Louis) maintains its own construction crew that is used to build bridge projects (>1 each year).

Despite a negative perception of timber bridges by some engineers and owners, this project clearly shows that there is potential in using timber bridge systems that are capable of being cost-competitive and long-lasting. The use of the enclosed design aids can help increase the awareness of modern timber systems that have excellent long-term performance.



Modern Minnesota Timber Bridges. The left bridge photo is a galvanized steel girder with transverse glued-laminated timber deck panels built by St. Louis County. The right bridge photo is a longitudinal dowel-laminated timber deck with metal spikes panelized bridge built by Hennepin County.

CHAPTER 1: INTRODUCTION

1.1 PROPOSAL SUMMARY AND OBJECTIVES

MnDOT data shows that only 25 timber beam or slab bridges were constructed in Minnesota from 2000 through 2019. During the same period, over 620 concrete slab spans or prestressed concrete beams bridges were constructed. This has occurred due to several factors, including misconceptions about the durability, structural adequacy and expense of constructing timber bridges. However, significant advancements in design, preservation, maintenance and inspection of modern timber bridges have been made. Recent national service-life assessment research has shown that timber is a durable option for primary structural members in highway bridges and can perform satisfactorily for 50 years or longer when properly designed, fabricated and maintained. However, both anecdotal assumptions and cost reports have indicated that timber bridges are more expensive than concrete bridges to construct (MnDOT, 2013).

The objective of this project was to develop a series of design, contracting and construction options and strategies for cost-competitive (initial and life-cycle costs), sustainable timber bridges in Minnesota that meet AASHTO HL-93 load requirements and LRFD Bridge Specifications. The project incorporated standard plans for timber bridge superstructures that are currently under development by USDA's Forest Service. These plans were evaluated and modified for Minnesota and when coupled with best inspection and maintenance procedures, provide new opportunities for constructing innovative, long-lasting and cost-competitive timber bridges. Finally, several bridge construction projects will be identified with partner counties that will use the developed plans, allowing the project team to assess and validate the true initial costs of construction, predict life-cycle costs, and complete a life-cycle assessment for these bridges.

The official project tasks were:

- | | |
|--------------|---|
| Task 1 | Literature Review, Project Review, Product Review, and Engineer Survey |
| Task 2 | Creation of Standard Superstructure Options |
| Task 3A, 3B: | Construction Projects and Partners to Demonstrate and Validate Cost-effective and High-Performance Timber Bridges |
| Task 4-6 | Preliminary and final reports, publication, and development of an in-person presentation for MCEA along with a webinar-based presentation. All products resulting from this work will be posted online through the National Center for Wood Transportation Structures (www.woodcenter.org), which is hosted by Iowa State University (a subcontractor on this project). |

CHAPTER 2: BACKGROUND ASSESSMENTS

2.1 LITERATURE REVIEW, PROJECT REVIEW, PRODUCT REVIEW, AND ENGINEER SURVEY

A comprehensive literature review was completed to identify previous research on modern, cost-effective, sustainable timber bridge superstructure plans, cost studies and assessment strategies for initial and life-cycle costs. Further, a review of timber bridge product, manufacturing and construction options was conducted to understand the available marketplace and construction market. To solicit information from county engineers, a survey was developed and distributed with a goal of understanding timber bridge concerns, construction protocols for bridges, and the use of county crews or engineering construction firms.

2.1.1 Literature Review

A comprehensive literature review was conducted through the University of Minnesota Duluth and the USDA Forest Products Laboratory to identify appropriate literature regarding timber bridges using the following terms: timber, vehicle bridges, cost, economics, materials, construction, superstructure, substructure, initial cost, life-cycle, maintenance, repairs, longevity, durability, design life, comparison cost, unit cost, Minnesota, and standard plans.

Based on this review, specific articles were collected and reviewed. Each of the following sections provides a summary overview of selected literature and the references cited. Within each section, they are not reported in a prioritized order. These sections included timber bridge plans, cost-effectiveness/cost studies, maintenance and environmental considerations and life-cycle assessment.

2.1.1.1 Timber Bridge Designs and Plans

Ritter (1990) composed a book summarizing all aspects of timber bridges. The material in this book include timber bridge history, wood mechanical properties, design options, and maintenance and rehabilitation methods.

Lee et al. (1995) developed standard plans for bridges utilizing southern pine. Three bridge superstructure types are included in the report: stress-laminated sawn timber, stress-laminated glulam, and longitudinal sawn stringer bridges with transverse plank. Various dimensional combinations for the timber bridges are included that meet AASHTO standards and specific load ratings.

Smith et al. (1995) conducted an analysis of the factors affecting timber selection for a bridge material. This report included information on criteria that were used to evaluate bridge material such as expected life and initial cost. A survey was sent to over 1,300 highway officials in 28 states asking to rank the level of importance for a variety of nonstructural factors that could be used in making bridge decisions. It was concluded that highway officials select prestressed and reinforced concrete over 70% of the time when deciding materials. This was credited to maintenance requirements, initial cost, and past performance carrying the most weight during material selection. The authors go on to discuss new advances in timber and the need for renewed education as it is now a more competitive bridge option.

Ritter et al. (1995) of the US Forest Service created plans for crash-tested bridge railings for longitudinal wood decks. The document includes the following design plans: glulam timber rail with curb (AASHTO Performance Level 1), glulam timber rail without curb (AASHTO Performance Level 1), steel rail (AASHTO Performance Level 1), steel rail (AASHTO Performance Level 2), and glulam timber rail with curb (NCHRP 350 Test Level 4). The plan diagrams include the following superstructure components: railing details, steel post plate, internal steel plate, rail splice details, curb splice details, approach rail transition configuration, transition block, transition connection details, curb transition, transition glulam rail boring details, and steel transition plate.

Tingley et al. (1996) of the Wood Science and Technology Institute monitored a long span (162 ft) timber glulam bridge for strain that was reinforced with fiber reinforced plastic (FRP). Three main girders (two exterior and one interior) were fitted with internal strain gauges and data was collected every 108 minutes for 70 days. The results indicated significant strength increase in the glulam bridges. According to the report this allows for a reduction in bridge cost due to lower grade substitution, smaller glulam dimensions necessary, and less transportation weight.

Spradlin and Smith (1997) of Virginia Polytechnic Institute published a report on market opportunities for wood in the United States transportation system. This technical report included how to incorporate the timber industry into a variety of product fields. These fields include highway guardrails, highway noise barrier, signs and signposts, formwork and falsework, railroads, marine wood pilings, electricity and communication transportation systems, and a section on preservative treated wood in transportation markets.

Ritter et al. (1998) of the US Forest Service produced plans for crash-tested bridge railings for longitudinal wood decks on low-volume roads. This document focuses on the need for low-volume railing designs due to timber bridges being used in rural locations. The document includes the following design plans: top-mounted railing (NCHRP 350 Test Level 1), side-mounted breakaway railing (NCHRP 350 Test Level 1), curb railing (NCHRP 350 Test Level 1), and low-volume curb railing. The plan diagrams include the general railing and curb details along with component details such as posts, post attachments, scupper block, curb splice, etc.

Ritter et al. (1998) of the US Forest Service produced plans for crash-tested wood bridge railings for concrete decks. The railing and curb plan used glulam as the timber material and each design section in the report is associated with a test level depending on the road traffic of the bridge. Timber rail attachment to the concrete deck was emphasized throughout the plans. Overall the report contains seven design options with different combinations of railing/curb or railing/no curb along with various test levels.

Faller et al. (2000) of the US Forest Service conducted tests on bridge railings for transverse timber deck bridges. The scope of the study involved two test bridges in areas with higher traffic (Test Level 4). The first bridge used a glulam railing system and the second railing used a steel tie-beam system. The testing criteria were in accordance with NCHRP Report 350 which requires three full-scale crash tests with varying vehicle speeds and weights. Another step for testing was to design the railings to meet

standards; all railing diagrams are included in the report. Sensors were installed throughout the railing systems to measure the forces and strain on the materials. The results indicated that both railing designs met the NCHRP Report 350 Test Level 4 requirements.

Pliemann (2000) conducted a study on three types of pre-designed timber bridges for Arkansas county roads. This study compared timber bridge performance vs. concrete and steel. It showed that concrete and steel bridges were deteriorating due to deicer chemicals and maintenance problems. The bridges chosen were the following: solid sawn stringers with transverse solid sawn deck, glulam stringers with transverse glulam deck, and stress-laminated full-span glulam stringers. The results are given in the form of tables listing appropriate spans and live loads correlated with timber designs. The report concluded that by following these recommendations these timber bridges should last 75 years.

Wacker and Smith (2001) from the US Forest Service published a report on standard timber bridge plans. The plans listed in the report consist of five longitudinal deck superstructure designs and two beam superstructure designs. The given plans follow AASHTO standards and the designs are associated with different loading and deflection values.

Faller et al. (2001) of the US Forest Service conducted tests on bridge railings for transverse glulam timber deck bridges. The scope of the study involved two test bridges in areas with moderate traffic (Test Level 2). The first bridge tested was a steel three-beam system, the second was a glulam timber railing system. The testing criteria were in accordance with NCHRP Report 350 Test Level 2, which requires two full-scale crash tests with varying vehicle speeds and weights. Another step for testing was to design the railings to meet standards; all railing diagrams are included in the report. Sensors were installed throughout the railing systems to measure the forces and strain on the materials. The results indicated the steel system met NCHRP standards with all steel members staying intact after the crash. The timber railing system also met the NCHRP standards with its components all intact and serviceable after the crash.

Pierce, a Sr. (2010) Principal Engineer for CHA Incorporated, prepared a technical report on heavy timber decks on steel beam bridges. This report discussed the advancements of the nail-laminated deck panels and glulam panels for New York State. This report discusses the engineering, availability, constructability, construction duration, durability, maintenance experience, and costs of these timber deck bridges. Details of standard deck installation and geometry are included along with common deterioration problems.

Araki et al. (2010) conducted a study on timber bridge durability. The five areas of influence that this report includes are material durability and antiseptic methods, climate, structures, design, and construction. Each influence is a factor in equations that predict timber bridge sustainability. Tables are listed in the report with specific numerical values for each focus area dependent on bridge characteristics such as wood species or treatment. They conclude in their report that although their data set is small, the predicted lifetimes and actual observed ones for the bridges they studied were similar.

Correia et al. (2013) of the University of Sao Paulo, Brazil conducted a study on the use of geosynthetics on asphalt wearing surfaces for timber bridge decks. The study emphasized that currently there is high

deflection, displacement, and shrinkage in timber under bridge asphalt. The research integrated geosynthetics into the wear layer as a water sealant and to provide rigidity. A case study was created when a geosynthetic layer was put into a modern timber bridge. The results indicated that the geosynthetic was successful at limiting reflective cracking and minimizing water exposure in the timber deck.

The Pennsylvania Department of Transportation (2013) provided design schematics for a 33-foot-long glulam timber bridge.

Scharmacher et al. (2014) developed a specifications report on different asphalt systems based on studies of timber bridges. The studies emphasized the adhesion between the asphalt and timber surface, and it was concluded that this adhesion is comparable to steel and concrete surfaces. Their technical conclusion for future surfacing was to seal with a vapor proof surface coating prior to installation or to use hot asphalt.

Gilham (2015) a chief engineer for Western Wood Structures Incorporated, composed a paper focused on creating a new perspective on timber bridges. The paper confronts common assumptions about timber bridge environmental challenges, durability, design options, etc. There are nine categories discussed: longevity, strength, span length, rail systems, wear surfaces, environmental considerations, economics, aesthetics, and sustainability. The report concludes that timber bridges are more than adequate as a construction option.

Chapter 8 of Wood Structures (MnDOT, 2015) contains information on timber bridge LRFD design. This section contains information relating to longitudinal and transverse decks, glulam beams, and pile caps; all specifications follow AASHTO LRFD requirements. Throughout the report there are design examples that are followed through with bending moment, bearing, shear, etc. calculations. The example bridges feature two deck types; transverse spike-laminated and transverse glulam.

Wacker and Smith (2016 – in progress) are working to development of standard plans for glulam timber bridges. In this study, they will develop updated and standardized design information for glulam highway bridges in accordance with the latest American Association of State Highway and Transportation Officials AASHTO–LRFD Bridge Design Specifications. Four different superstructure types are included: longitudinal glulam deck, stress-laminated glulam longitudinal deck, transverse glulam deck on longitudinal glulam girders, and transverse glulam deck for longitudinal steel girders. The primary output from this project will be an updated and user-friendly set of standard bridge design aids for glulam timber highway bridges. They will be available to the general public in a variety of forms through the National Center for Wood Transportation Structures website including electronic (PDF) versions of the as-printed publication, AutoCAD drawings available for download, and design example calculations derived in MathCAD (PDF) for each bridge type.

2.1.1.2 Cost effectiveness, Cost studies

A technical report prepared by Frangopol and Liu (2004) investigated the accomplishments and challenges of life-cycle cost analysis for highway bridges. Their research involved using current Bridge

Management Systems (BMS) along with BRIDGIT which is based on Markovian deterioration modeling. Their results display recent upgrades to BMS systems for calculated life-cycle costs of bridges.

Sarisley (1990) evaluated the methods and costs of stress-laminated timber bridge construction. Sarisley's method involved observing costs for a 50 ft long by 13 ft wide single-lane, two-span continuous bridge in Connecticut. All designs and materials were presented, and their associated costs are listed throughout the paper. Results showed a 32% savings in construction by using timber compared to the other alternatives of steel and concrete. The report also included suggestions to improve labor costs such as using pneumatic nailing and the prospect of using lower grade timber to decrease costs.

Orr et al. (2000) conducted a study on the costs of 327 timber bridges. 121 were demonstration projects, and 206 were not. The goal was to determine if there were cost differences between demonstration and non-demonstration bridges. The report shows the minimum, maximum, and average dollars per square meter accompanied by the number of bridges, bridge length, bridge width, and number of spans. The conclusion was that demonstration bridges cost approximately \$120 more per square meter of superstructure than non-demonstration bridges, a 36% increase in cost. It was also noted that the wood-steel stress-laminated design was the most expensive.

The US Forest Service (2001) conducted life-cycle cost analyses of timber vs. concrete, pre-stressed concrete, and steel. The study selected 36 of the 116 National Bridge Inventory (NBI) fields to be used as data. The superstructure cost, substructure cost, and total bridge cost was all incorporated in the study. The results of the study found that timber bridges were cheaper to install in the Midwest compared to the Northeast. It was also discovered that initial costs were similar between timber, concrete, and steel however there was high variability across all cost comparisons due to variation in construction designs.

The US Forest Service (2011) has a standard guide for costs of bridge construction. The guide consists of tables with each component of the bridge being given in price per square foot or linear foot. The report includes a table directly comparing timber and steel pile costs along with beam costs of prestressed concrete. It also includes a detailed table of timber railing costs by component.

A poster from the Forest Service (2003) that describes four timber bridge projects and their total costs. The three bridge types include one glulam and two sawn lumber. All three bridges are one span, utilized Red Pine, and treated with CCA while having varying lengths and widths (all under 32 ft in length). The three bridges ranged in cost from \$46,000-\$285,900.

A master's thesis by Sowards (1998) reported a comparison of initial superstructure costs of timber bridges to those of steel, concrete, and prestressed concrete. Sowards method included using data from the NBI databases to retrieve bridge characteristics along with their costs. Data collection for costs was broken down into cost per square foot and plotted against the following factors: structure length, maximum span length, and width. Other costs plots were reported incorporating construction type, load rating, year constructed, and region. The results were that timber bridges are cost competitive with steel and concrete superstructure initial costs.

Sowards et al. (1998) of Michigan Technological University conducted a cost study of timber bridges to compare them to steel, concrete, and prestressed concrete. There were 1604 bridges (all built after 1980) identified for survey throughout the country that were found using the NBI database. Surveys inquiring about costs were sent to all 1604 bridges and later analyzed to determine costs with load ratings and span lengths as factors. The authors concluded that there was a parabolic shape between cost and short and long spans along with a positive relationship between unit cost and load rating. The main consensus was that there is high variability in timber bridge costs which might be caused by unspecified cost factors, lack of standardization in construction, and the realization that timber bridges found their market niche.

Smith and Bush (1995) published a paper through the USDA Forest Service involving research on the factors influencing the adoption of timber bridges. Research on this topic emphasized the timber market and economy. This paper consisted of a literature review of the current factors limiting the market for timber. It was concluded that the best way to understand this complex issue is to understand the decision-making process for bridge material selection.

Verna et al. (1984) prepared a technical report on the benefits and costs of timber bridges. The issue presented in this paper is deicing agents on bridges and the costs of substituting timber bridges for their immunity to deicing damage. Three cases were studied containing the following bridge types: deck replacement over steel girders, beam and deck replacement using existing abutments, and a replacement of a railroad overpass. The three cases studied yielded these results: timber is resistant to deicing agents and has low maintenance costs, it is easier to transport and handle, and timber can be more economical if components such as abutments or beams can be recycled.

Behr et al. (1990) conducted a study which compared the cost of timber, steel, and prestressed concrete bridges. Their method involved compiling initial superstructure costs of timber, steel/concrete, and prestressed concrete bridges at 20-, 40-, and 60-ft spans (all within New England area). Their report concluded that in this short span range of 20- to 60-ft timber is competitive with other bridge material options. The biggest savings for timber compared to alternatives was in the labor estimates category.

Dickson (1995) of West Virginia University conducted a technical report on timber bridges in West Virginia. Volume I includes case studies that lists the type, dimensions, year built, and superstructure/total costs of 53 bridges. Volume II lists a summary of each of the 53 bridges which includes: geometry, materials, local economic impact, bridge performance, and fabrication and erection.

Smith and Bush (1996) composed a technical report on the nonstructural factors that influence bridge material selection. Three groups of decision-making groups were selected: State DOT engineers, private consulting engineers, and local highway officials. After data was collected an analysis of variance between decision-maker groups, materials, and geographic regions was conducted. Tables listing performance scores by these three focus groups for each bridge type was included. The results were concluded to say that timber was perceived as appropriate for use in short span rural areas where road salt is corrosive to timber and steel.

Szakats and Butcher conducted a study on the design and capital cost of a 158-foot glulam bridge. The bridge consisted of two trusses, a concrete deck, and glulam beams (bridge schematics are included). It was compared against an alternative steel bridge for cost analyses. The study found that the timber bridge was less expensive for abutment costs but 30% more expensive for superstructure costs. The paper then discussed cost effective timber bridge design. This included having joints with more connectors, lightweight decking systems, and composite action between reinforced concrete decks and timber beams to reduce shrinkage and thermal effects.

Rautakopri et al. (1993) published a report through the Helsinki University of Technology on the development of wood bridges (1993). Girder, arch, cable-stayed, truss, and box-type bridges were all studied. Material properties and span vs. wood quantity were discussed in depth throughout the report for each bridge type along with bridge dimensions and designs. The report concluded that composite girder bridges with glulam beams and a concrete deck should increase in development due to being economical bridges.

The Transportation Research Board (1995) published a report on steel, concrete, and wood bridges. This study includes sections on load ratings, superstructure design, and the performance of bridges with interlayer membranes. The study on the bridge membranes concluded that the poorest performance came from bridges that used polypropylene and a coal tar sheet system.

Smith and Bush (1995) conducted a study on the factors affecting the adoption of timber bridges. In the study a survey was sent out to timber bridge manufacturers to determine sales to bridge projects. County and State entities also received surveys on timber bridge expenses and attitudes towards implementing them. Four states were chosen for these surveys and they included: Mississippi, Virginia, Washington, and Wisconsin. The results showed an average total bridge cost ranging from \$30 to \$70 per square foot. A table in the report also listed the bridges expected life spans, the number of bridges built between 1985 and 1992, the number of deficient timber bridges, if the state has standard timber bridge plans, number of wood treating plants, and timber resource.

Smith and Bush (1995) conducted a study of marketing practices of timber manufacturers related to the timber bridge industry. This entailed sending questionnaires to various firms; 31 companies ending up being chosen as relevant sources for the questions. Polls were also sent out to highway officials, DOT branches, etc. to find important topics for choosing bridge material. The results of the study show that decision makers focus more on long-term performance and maintenance costs while timber bridge advocates focus on the initial costs (timber bridges being less expensive initially).

Amburgey et al. (1994) conducted a study on the potential to produce prefabricated timber bridge components in Mississippi. This report consisted of the current status of Mississippi bridges, the historical development of timber bridges, the advantages of modern timber bridges, a cost analysis on manufacturing timber components, the impact of timber bridges on the timber industry, etc. Results of the study show operating expenses of timber bridge manufacturers along with costs of timber structures.

George Banzhaf and Company (1994) conducted a study on timber bridge potential in the state of Wisconsin. The goal of the study was to investigate the size of the timber bridge market, the attitude towards it, and to create a database of recent timber bridge projects. County, township, forestry, timber bridge manufacturers, and researchers were all sent a questionnaire inquiring about viewpoints towards prestressed concrete, reinforced concrete, steel, and timber bridges. Most responses emphasized life expectancy and cost effectiveness as reasons for choosing concrete over timber. The report includes multiple tables organized by county describing bridge projects with what material was chosen. The report concludes with bulleted strong and weak advantages of timber bridges according to the surveyed responses. The actual surveys used were included in the appendix.

The State Aid for Local Transportation Manual (2015) provides info on funding for local programs. This document discusses the Federal Highway Bridge Replacement and Rehabilitation Program (HBRRP), State Transportation Fund (Bridge Bonds), Town Bridge Program, Selection of Bridge Projects and Application for Bridge Funds, Plan and Grant Approval, Eligible Costs and Cost Split Determination, Payments, and the Advancing Town Bridge Funds. These program sections list the prerequisites for funding such as bridge length, expenses, bridge components, etc. There is a table that lists all components of bridge installation and associates them with funding eligibility from multiple programs.

Quintana and Coole (1994) of the USDA Forest Service composed a report on timber bridge superstructure costs on project funded bridges from 1989-1994. This is a cumulative report that lists average regional costs of superstructures by region, type (example: stress laminated or longitudinal glulam), length, and wood species. Results of each area along with associated graphs are listed in the report.

Pilon (1995) of the Michigan Department of Natural Resources created a report on manufacturing and marketing opportunities for modern timber bridges in Michigan. The method for this research involved sending surveys to different parties involved in bridge construction. The survey asked about general material uses and their performance along with their perspective on timber as a bridge material. Most responded with a high preference towards prestressed concrete as a bridge material. Tables were included in the report with percentages of importance for factors such as life costs, durability, resistance to salt, initial cost, etc. when selecting construction material. The report summed up what situations the respondents would use concrete, steel, or timber. It was noted that 31% didn't know what the best preservative for timber bridges was.

Gerold (2006) conducted a study on the economic efficiency of modern timber bridges. The research involved 56 protected (enclosed by a roof or with asphalt cover) timber bridges built within the last 20 years; all the bridges were built in Germany in all climatic regions. Notes are included in the report concerning various design ideas such as fiber orientation of the wood, sheet metal cover geometry, and asphalt applications. The study concluded with statistics on the maintenance costs of the covered bridges. The costs (as percentages of the construction costs) ranged from 0.6% to 0.7%. The lower percentages were due to the main bridge beams being protected from both the top and sides while the higher costs were from just asphalt sealant. It was concluded that these maintenance costs were comparable to that of steel and concrete.

2.1.1.3 Maintenance and Environmental Considerations

A research project completed by Phares et al. (2015) of Iowa State University created a manual for cost-effective timber bridge repairs for Minnesota timber bridges. The report outlines timber bridges in Minnesota, condition assessment options, preventative maintenance options, rehabilitation procedures, cost estimates, and other potential repair methods. The cost estimates for repair include price per square or linear foot depending on the repair.

A technical report prepared by Brooks (2000) discussed and compared the environmental effects of creosote, pentachlorophenol, and chromated copper arsenate. Two bridges with each treatment were examined for risk assessment. The results were concluded to be minimal to the surrounding biological ecosystem; creosote was the only treatment that reached the threshold effect level in sediments downriver (Brooks, 2000).

Ainge (2012) of Marquette University composed a master thesis on the repair and strengthening of bridge superstructure. The goal was to address the repair issues in Wisconsin bridges. The deterioration affecting concrete, steel, and timber is expansion joint degradation, which Ainge reports is predominantly caused by deicing chemicals. A wide variety of repairs for a variety of substructure problems are described for each bridge type. Ainge concludes that concrete warrants the most repairs due to deicing problems.

Johnson (undated) of Wheeler Lumber wrote a report on repair and rehabilitation of treated timber bridges. The report is separated into the following categories: material, inspection, repair, and rehabilitation. After these categories are discussed there are six different bridge projects that are used as examples; total repair costs are also given with the projects.

LaDoux and Bernhardt (2015) of the Western Wood Preservers Institute reported on creative and sustainable timber bridges using treated wood. Their report is structured around studying risk management and how to determine the appropriate preservative for different scenarios. The treatments discussed are Chromated Copper Arsenate (CCA), Pentachlorophenol (PCP) and Copper Naphthenate (CuN). The paper discusses how to select the proper preservative, environmental considerations, best management practices, quality assurance, and maintenance guidelines. They concluded their report by saying the contents of their paper include two decades of research and case studies, and that the guidelines given should allow for proper treatment selection.

Franke et al. (2013) of Bern University of Applied Sciences, Architecture, Wood and Civil Engineering conducted a study on the long term performance of timber bridges. Their emphasis was on moisture effects in different directions (longitudinal and axial) over time and how they affect bridge load capacity and serviceability. The method for this study was to have probes on four timber bridges in Switzerland for 25 months. The study concluded first that electrical resistance probes can measure long term moisture of timber bridges. It was also discovered that wood in the bridges does change moisture with the climate and that these variations change less the further from the surface the timber is. In the climate measured the moisture contents ranged from 12% to 22% for the outer layers. It was suggested that this kind of monitoring helps prevent decaying and structural defects in the bridge.

Dickson (1996) of West Virginia University conducted a technical report on the obstacles and opportunities of engineered wood products. The goal of this report was to discuss all the factors that play into selecting wood products. The method for this study was to have facilitated workshops with engineers, manufacturers, etc. with various topics. The timber bridge topics discussed at these workshops included: material characterization, design, construction, economics, technology transfer, and environmental effects. The key points discussed in these workshops are listed throughout the report. The study concluded the report by stating that an engineered wood planning committee was formed that was tasked with developing this area of industry.

Smith et al. (1998) of the Center for Forest Products, Marketing, and Management at the Virginia Polytechnic Institute carried out a study on the perceptions of rural timber bridges in 28 states. Their objective was to discover how the different parties (DOT, private consultants, etc.) viewed timber bridges and what factors were causing the discrepancies; an example of this would be if perception changed by education or geography. Questionnaires were sent to various institutions asking about general experiences with timber bridges. The results of the study were that timber rated the lowest on performance compared to other materials other than in the constructability area. Possible explanations for these perceptions were explored such as region (the South having higher decay rates) playing a role and previous poor timber designs leading to stereotyping. The authors noted that education about the performance of properly designed timber bridges must be shared with the engineering community.

2.1.1.4 Life-Cycle Assessment

Hammervold et al. (2013) prepared a report of a life-cycle analyses of 24 bridges with varying materials. The report findings showed wooden bridges having substantially less global warming potential and abiotic depletion potential as compared to steel and concrete. A table was presented listing global greenhouse gas emissions per square meter across bridge types such as concrete slab and girder, steel slab and girder, and wooden arch. Specific material components and their greenhouse gas emissions are also listed; examples would be creosote impregnation for timber, reinforcement for steel, mastic for concrete. The report concludes that steel bridges have the highest impact due to energy intensive production.

Svanaes (2010) of Norsk Treteknisk Institutt analyzed and presented on the environmental impacts of various wood treatments used for bridges. The environmental aspects included: global warming potential, ozone layer depletion, photochemical oxidation, acidification, eutrophication, and human toxicity. These were compared between the following sawn wood treatments: no treatment, painted four times, copper impregnated timber, creosote impregnated timber, and painted timber gate. The highest contributors were found to be the creosote and those painted four times (i.e., four coats of paint).

A master thesis by Dequidt (2012) studied the life-cycle assessment of a Norwegian bridge. His life-cycle analysis followed ISO standards and measured the greenhouse emissions of the Norwegian bridge along with including literature of previous environmental analysis. Dequidt concluded that concrete was the

biggest contributor to greenhouse gases and that the production phase (compared to construction and maintenance) accounted for most emissions.

Bergman et al. (2014) reported on a life-cycle analysis of timber superstructures vs. steel. Two wood (one alkaline copper quaternary (ACQ), one creosote treated) and two steel designs were studied, both 80 feet long. The following environmental aspects were analyzed: Fossil fuel consumption, global warming potential (GWP), ozone depletion potential (ODP), smog potential (SP), and eutrophication potential (EP). Ozone depletion and eutrophication potential were heavily influenced by creosote but not ACQ treatment or steel structures. Homogenous steel had significantly heavier impacts to the environment in the all other categories compared to timber bridges and lightweight steel.

A master thesis by Dugdale (2015) laid out a method to compare timber and steel superstructures through a structural, economic, and environmental lens. This report focused on single span highway bridges in Vermont with steel and glulam bridges being analyzed. Economic results indicated that some costs can be predicted but all bridges studied were too different with a wide range of labor costs. The environmental results indicate that timber is more difficult to recycle than steel. It was also noted that carbon emissions from the *Inventory of Carbon and Energy Database* with the given weight of materials could be used to calculate environmental impact between the two materials.

A master's thesis by Dimopoulou in 2015 studied the life-cycle assessment (LCA) and life-cycle cost (LCC) analyses of three pedestrian bridges design (timber, steel, and fiber reinforced polymer) in Sweden. The thesis used software *BridgeLCA*, *OpenLCA*, *Excel*, and *Ecoinvent* database to calculate the analyses, and concluded that the main impacts in a pedestrian bridge derived from the initial phase for LCA and LCC, and the most financial efficient material was timber in a life-cycle perspective, and timber was found to be the material with less effect to the environment.

A technical report prepared by Virginia Transportation Research Council in 2002 surveyed the timber bridges built in Virginia, and concluded that they had not been shown to be economically-competitive from a first cost standpoint, and life-cycle cost data could not be determined at that time (McKee and Gomez, 2002).

Morcous (2013) of the Nebraska Department of Roads conducted a life-cycle cost analysis (LCCA) using RealCost software to assess investment decisions and identify the most cost-effective improvement alternatives for different maintenance strategies using the developed deterioration models and updated cost data for Nebraska bridges. However, no timber bridges were analyzed using LCCA software.

A technical report prepared by URS Corporation for Massachusetts Department of Transportation in 2011, surveyed five bridge scenarios on function, safety, and life-cycle cost analysis (LCCA) for potential replacement alternatives, and concluded that the concrete and steel hybrid bridge is the most favorable that achieve an appropriate balance of all design criteria. The more timber materials used the less favorable.

Rodrigues et al. (2014) conducted a sustainability assessment of life cycle environmental and economical assessment of Timber-Concrete Composite (TCC) deck as potential alternative and

concluded that TCC solutions have less environmental impact and are economically competitive. The CML 2001 method was followed, which considered Abiotic Depletion (AD), Acidification (AC), Eutrophication (EU), Global Warming (GW), Ozone-layer Depletion (OD) and Photochemical Oxidation (PO). The LCA study used SigmaPro software, and the economic study was based on the ISO standard 15686-5 that covered agency cost, user cost, and third-party cost.

Du and Karoumi (2012) conducted a literature survey about the LCA implementation for railway bridges that focused on the methodology, practical operational issues and data collections, and proposed a systematic LCA framework for quantifying environmental impacts for railway bridges.

Bolin and Smith (2011) studied the cradle-to-grave LCA of alkaline copper quaternary (ACQ) treated lumber with wood plastic composite decking as comparison. Results found that ACQ treated lumber impacts were fourteen times less for fossil fuel use, almost three times less for GHG emissions, potential smog emissions, and water use, four times less for acidification, and almost half for ecological toxicity than those for WPC decking. Impacts were approximately equal for eutrophication.

Bolin and Smith (2011) studied the cradle-to-grave LCA of pentachlorophenol treated wooden utility poles with steel and concrete utility poles as comparisons. Results found that the GHG, fossil fuel use, acidification, water use, eutrophication, and ecological toxicity impact indicator values for penta-treated poles are less than those for concrete poles. The GHG, fossil fuel use, acidification, water use, and ecological toxicity impact indicator values for penta-treated poles are less than those for steel poles. The values are about equal for eutrophication. The smog impact from penta-treated poles is greater than the smog impact from both concrete and steel poles.

Du et al. (2014) studied the LCA as decision support tool for bridge procurement with five different steel and concrete designs, which provided vital knowledge guiding the decision maker to select the most LCA-feasible proposal and mitigate the environmental burden in the early stage.

Du and Karoumi (2013) conducted an LCA of two different superstructure designs of railway bridge and concluded that the maintenance scenario planning and steel recycling have the significant influence on the final results other than the traffic disturbances.

Donnelly of Old Post Consulting published a report encompassing all aspects of timber bridges. This report was a guide that included the timber bridge parts, types, wood construction materials, design standards, lumber grading, native lumber, preservative options, additional bridge elements such as guardrails, financial considerations, and finally the steps for choosing how to build a timber bridge. This last section was followed by three case-studies of timber bridges which included detailed information on all components and the final price of the bridge.

2.1.2 Timber Bridge Projects

A variety of project plans and information were obtained from the literature, from MnDOT State Aid, from bridge component suppliers and directly from counties.

The Pennsylvania Department of Transportation (2013) provides all design schematics for a 33-foot-long glulam timber bridge.

MnDOT State Aid shared a document that consists of the bridge plan for number 11526 of Cass County (2012). This bridge was a three-span bridge totaling 54 feet in length. It had a timber panel superstructure and all component costs are listed in a table. They also provided a document is from Watonwan County (2010) that contains timber bridge blueprints along with a price table listing all components. The bridge has three (30-foot) spans and the deck includes shiplap joints.

A table of timber bridge projects was provided by Wheeler Consolidated (2016) that listed the order number, customer, owner, project, comments that include dimensions, etc. All projects are from 2010-2015.

2.1.3 Timber Bridge Suppliers

2.1.3.1 Wheeler Bridge and Highway Products, Eden Prairie, MN

An initial project meeting and site visit was held with Wheeler Bridge and Highway Products Division and Erickson Engineering. Started in 1892, Wheeler provides building materials and related services that serve both public and private infrastructures. Wheeler combines engineering, manufacturing experience, and the proven capability of treated wood to offer a variety of highway related solutions. These include timber bridge spike-laminated panel system (Panel-Lam), nail-laminated and glue-laminated (glulam) transverse timber decks, glulam beams, and various steel components. Several documents were provided by Wheeler (2011, 2011, and 2015). Specific details on these bridges are in Appendix A. Wheeler owns a copper naphthenate wood treating and production plant located in Whitewood, South Dakota, and they utilize Peterson Treating in Superior, WI for waterborne treating of components.

Wheeler timber bridges has a pamphlet on steel stringer bridges with timber decks. Some features listed are that their timber railings meet AASHTO (NCHRP-350) crash test guidelines and that the ship-lapped panel connection improves asphalt wearing surface performance. It is also discussed that the bridge can be shipped as a kit, allowing for fast installation.

Typically, Wheeler is involved with 30-40 timber highway bridge projects annually within the US, and notes that pre-cast concrete box culverts are one of the primary products that they are now competing against. Competitive timber bridge projects typically include span lengths <30 ft, constructed on low-volume rural roads, where rural construction with ready-mix concrete is more expensive, and where a short construction window is needed due to long detours or other factors.

They make a significant effort to engage and work with local bridge owners, but still noted a need to further educate county engineers that timber can be a structurally sound, long-lasting, and cost-effective solution. They have reported that few customers are concerned with environmental considerations for timber, such as timber being a renewable resource that sequesters carbon, the low energy or carbon emissions from production of timber versus high energy and carbon emissions from

steel or concrete materials. They have not been able to sell life-cycle costs or life-cycle assessments to local bridge owners.

Other discussion points during the meeting included bituminous deterioration (cracking and pitting) concerns on bridge decks, the potential for using timber in winter construction projects, the need to streamline preservative approvals, the lack of timber projects for contractors resulting in marked-up costs, and that Minnesota has very few counties remaining with their own construction crews. Any improvements in improved water management design details, low-cost railing designs, or construction details need to be contractor sensitive and keep costs down.

One topic was the process that county engineers use to get copper-naphthenate approved for use in county bridge projects. It was reported that there is a fair amount of back and forth associated with getting MnDOT State Aid to waive the approval for this preservative to the county. MnDOT currently has a Treated Wood Waiver Form Template (<http://www.dot.state.mn.us/stateaid/bridge/wood-treatment.html>) available to help streamline their wood preservative approval process. It was also asked that MnDOT consider including education about wood preservatives, timber bridge products, timber bridge performance and other timber aspects during special training meetings which include county engineers and local bridge owners.

Considerable discussion revolved around the construction materials and manufacturing process used by Wheeler and how it drives costs. Douglas-fir is the primary construction material used by wheeler and is most often treated with copper-naphthenate. Douglas-fir materials are purchased by volume through brokers which benefits cost efficiency. They also buy dimension southern yellow pine for some projects, which is often treated with waterborne pentachlorophenol C. A tour of their production facilities for local bridge owners could be offered in the future by Wheeler to continue education potential MN customers.

As to bridge life, Wheeler indicated that they expect their project materials to last for 60-80 years minimum. Two new approaches are being implemented for mitigating the shortened service life of timber cap beams use at intermediate pier and abutment supports. Each of these new approached are aimed at providing a more robust treatment of these critical substructure components. Dual treatment, first with water-borne methods then followed by oil-borne pressure treatment, can provide a deeper penetration of preservatives to enhance the outer treated envelope of protection. Another option currently be implemented are diffusible borate preservatives introduced via strategically drilled holes that do not diminish member strength. The borate chemicals have the advantage of diffusing into the cap beams when water is present, and they can be replenished periodically to prevent premature deterioration.

They feel that one potential for cost-competitiveness is to be continually involved in the design process, and perhaps be more engaged in the development of superstructure and substructure design plans. This is a model they are doing in southwestern Wisconsin (Juneau, Clark, and Wood Counties), where Wheeler is developing the plans and the county crews are doing the construction.

As a final take-away, Wheeler noted that Minnesota poses challenges in getting timber bridges constructed, and that ongoing support and engagement from MnDOT State Aid Bridge is important to advance timber bridge construction in the state.

A comprehensive review of their firm and products can be found at: <http://www.wheeler-con.com/highway-bridges/>. A copy of several Wheeler publications, including *Transverse Deck Vehicle Bridges*, *Panel-Lam*, *Steel Stringer Vehicle Bridges*, *Timber as a Highway Bridge Material*, and *Rapid Construction with Timber Components* are available on their website.

2.1.3.2 Bell Structural Solutions/ALAMCO Wood Products, LLC

A site visit and meeting were held with staff from Bell Structural Solutions/ ALAMCO in New Brighton, Minnesota. Both businesses are divisions of Bell Lumber & Pole Company. ALAMCO Wood Products is in Albert Lea, Minnesota and is a manufacturer of structural glued laminated timber beams and arches for many uses, including but not limited to churches, trusses, park shelters, bridges, and utility poles. Bell Structural Solutions focuses on the delivery of specialized and engineered solutions to the commercial marketplace including such items as gazebos, pavilions, shelters, amphitheaters, band shells, trellis / arbor / pergola structures, pedestrian and vehicle bridges, commercial and industrial straight or curved laminated wood beams. In addition, they offer piling, house logs, solid sawn timbers as well as several utility pole products.

ALAMCO primarily uses glulam materials in their bridge packages for both the girders, decks, and crash-tested railing systems and works with a 3rd party engineering firm to finalize production documents. They use pentachlorophenol A as their primary treatment after production and pentachlorophenol C if treated prior to lamination. They have their own treating plants in both Minnesota and Nebraska. They have conducted a lot of timber bridge projects across the United States, with a significant number of installations since 2000 in the northeast. They also have glulam timber bridges still in service in Minnesota, installed starting in the 1960s. Many glulam bridges from that era are in adjoining Blue Earth County.

In conversations with staff, they suggested the potential for reducing costs might lie in the development of standard plans that have blanket approvals and are considered peer-engineered. Further, this approach of bulk bridge packages could result in manufacturing efficiencies, the ability to prefabricate components in advance, and to get lower costs through bridge bundling packages. They also suggested the potential for wider construction programs with timber construction. Bell has already developed several packages of standard packages for 25, 35, and 50 ft.

A comprehensive review of Bell Lumber & Pole can be found at <http://www.blpole.com/>. Details about the services and products for ALAMCO can be found at <http://alamcowood.com/> and for Bell Structural Solutions at <http://bellstructural.com/>. A copy of the presentation on timber bridges and other relevant publications can be found in Appendix A.

Bell Structural Solutions promotes durability and sustainability. Their pamphlets list a 75-year lifespan for their glued laminated timber bridges treated with pentachlorophenol. They also list the fact that

deicing agents do not affect their structures along with them having the capability to handle AASHTO HS25 loading. For sustainability, Bell Structural Solutions utilizes smaller trees harvested of managed forests with an emphasis on reforestation.

2.1.4 Engineer Survey

A survey was developed for county engineers to gain additional perspective on the number and type of bridge replacement projects completed since 2005, to understand perceptions regarding potential selection of timber bridges, suggestions for cost-effective strategies, and to understand any life-cycle or environmental considerations used in bridge replacements. A listing of the survey questions is in Appendix B. This survey was sent to Minnesota county engineers and the final responses were collected, tabulated and reported in the final task report.

In April of 2016, Iowa State University conducted a survey of Minnesota County Engineers. The survey questioned the engineers about the types of bridges that they constructed, the reasons behind why that style of bridges were chosen, and the attitude and ideas that the engineers had toward timber bridges. A total of 45 engineers participated in this survey. The following report summarizes the results of this survey question by question.

Question 1: Please provide contact information.

Question 2: How many new and/or replacement bridges have you constructed since 2005?

Figure 2.1 shows the results of this question. Almost half of the engineers surveyed constructed 16 or more bridges during this time period. The remaining engineers all had constructed at least 1 bridge but were somewhat evenly distributed between 1 and 16 bridges constructed.

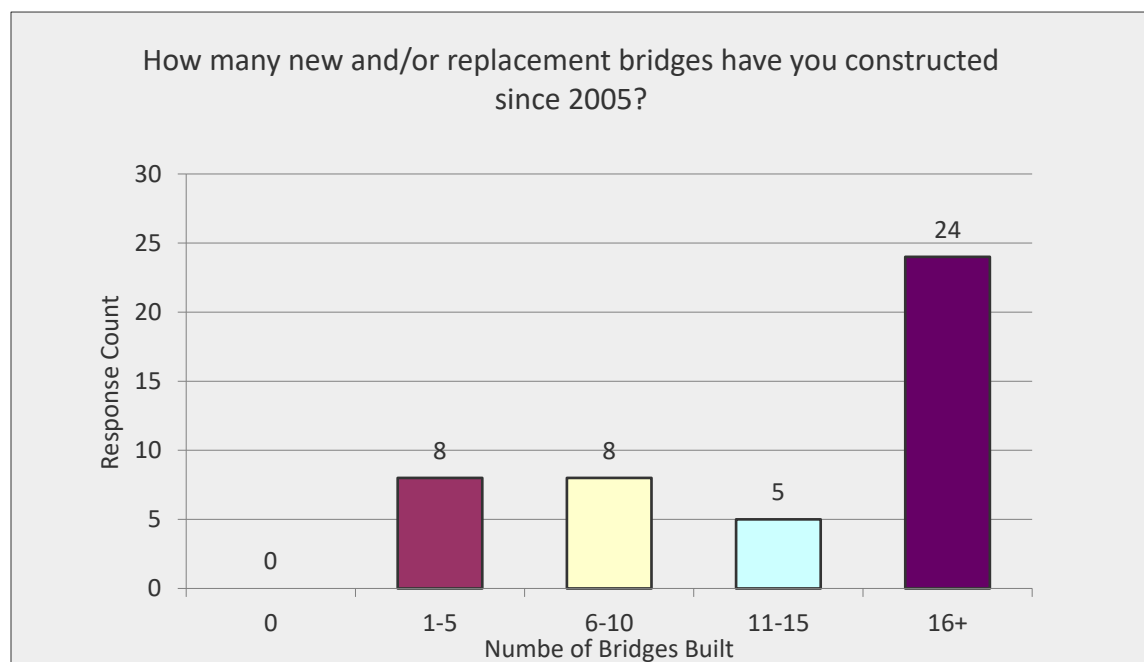


Figure 2.1 Number of bridges constructed by county from 2005 to 2016.

Question 3: How many of each of the following bridge types were constructed from 2005 to present?

Results are shown in Figure 2.2. The majority of bridges constructed were made of concrete. Timber and steel were used in constructing significantly fewer bridges.

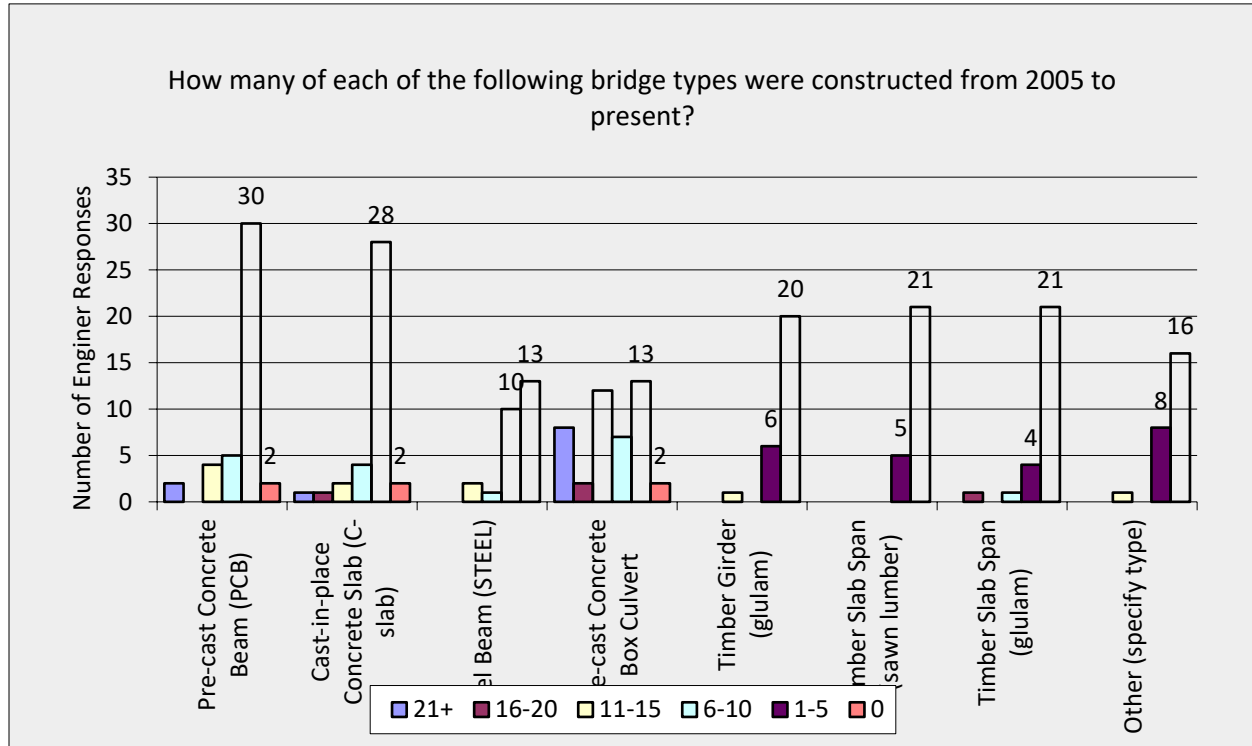


Figure 2.2 Bridges constructed by type between 2006 and 2016.

Question 4: If you have constructed a timber bridge or bridges since 2005, what factors played into your decision?

The results of this question can be seen in Figure 2.3. Though all possible responses were selected, the most common answer was “construction schedule requirements.” Additionally, it is apparent from looking at this data that those who answered this question had more than one reason for choosing a timber bridge, as many of the respondents selected two or more of the possible answers. Besides the fact that each possible answer was selected, this fact also further shows that wood can be chosen as a design product for a variety of reasons. Lastly, of those who selected “Other,” two answers were aesthetics and one was to pass debris.

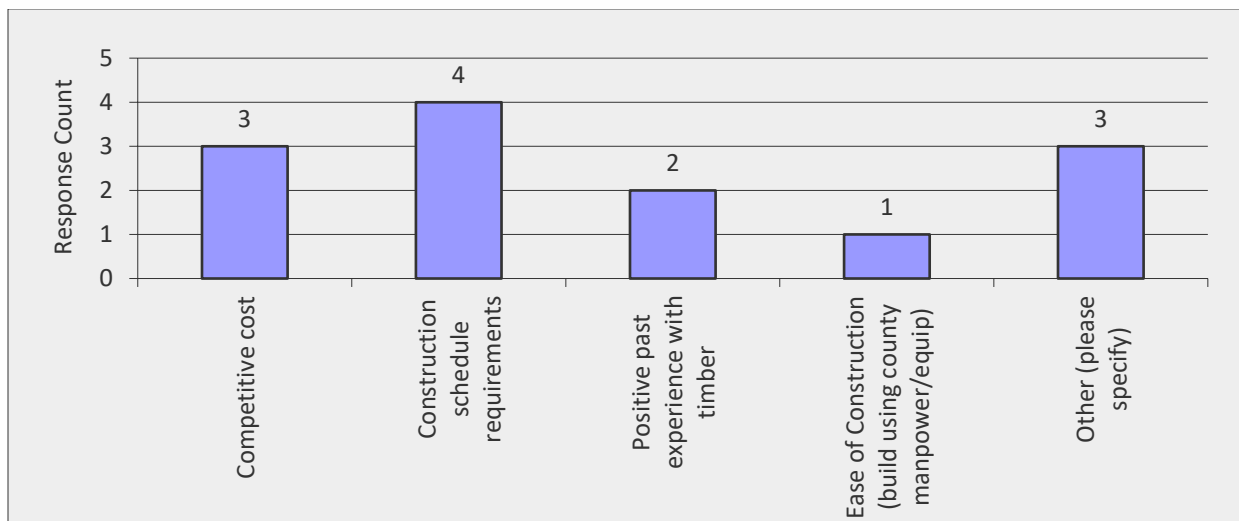


Figure 2.3 Factors that played into constructing a timber bridge between 2005 and 2016.

Question 5: Who designed the timber bridges that you constructed?

Figure 2.4 shows the result of this question. Most engineers who decided to go with a timber bridge used a consultant to design the bridge. Note that those who selected other simply stated that they did not construct timber bridges. None of the other data should be considered.

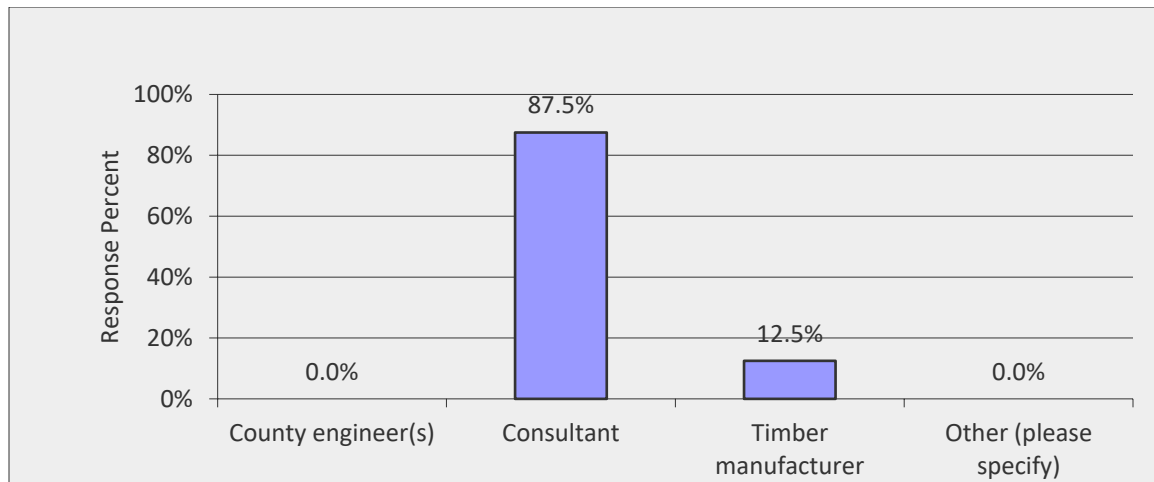


Figure 2.4 Respondent response to who designed the timber bridges constructed between 2005 and 2016.

Question 6: Who constructed the timber bridges that you built?

Engineers seemed to utilize both options; however, a majority chose to go with a contractor. It is also clear from the data that some of the engineers utilize both contractors and county crews, as some participants selected both options. The results are shown below in Figure 2.5.

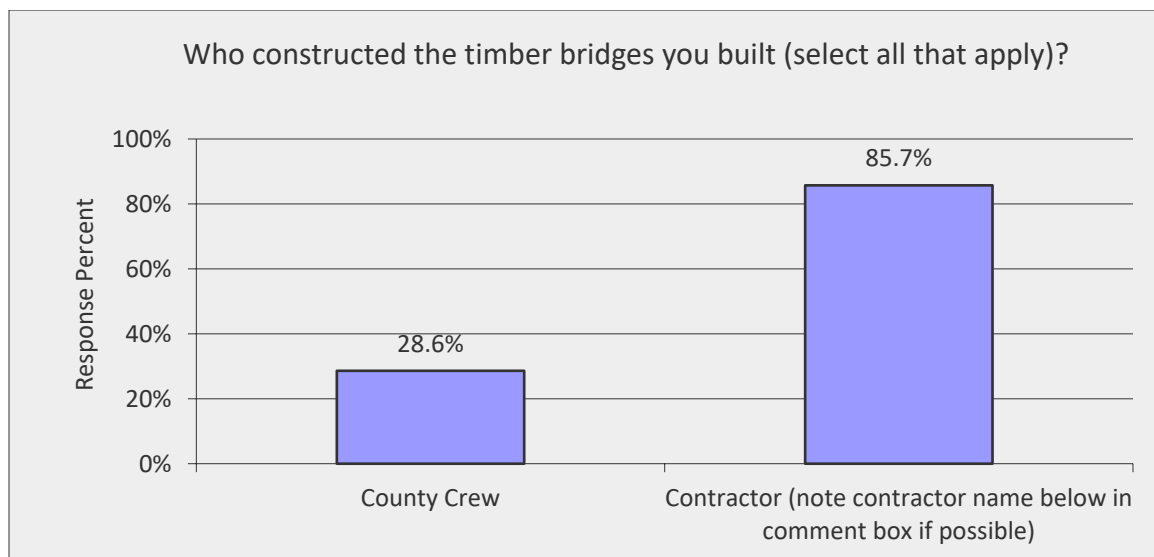


Figure 2.5 Construction labor used to construct timber bridges from 2005 to 2016.

Question 7: How were the timber bridge project(s) funded?

Figure 2.6 shows the results. It is apparent from the data that that most of the funding for timber bridges comes at the state level, although local funding is also important and a significant contributor. Also, it is apparent that the federal government funds very few timber bridge projects.

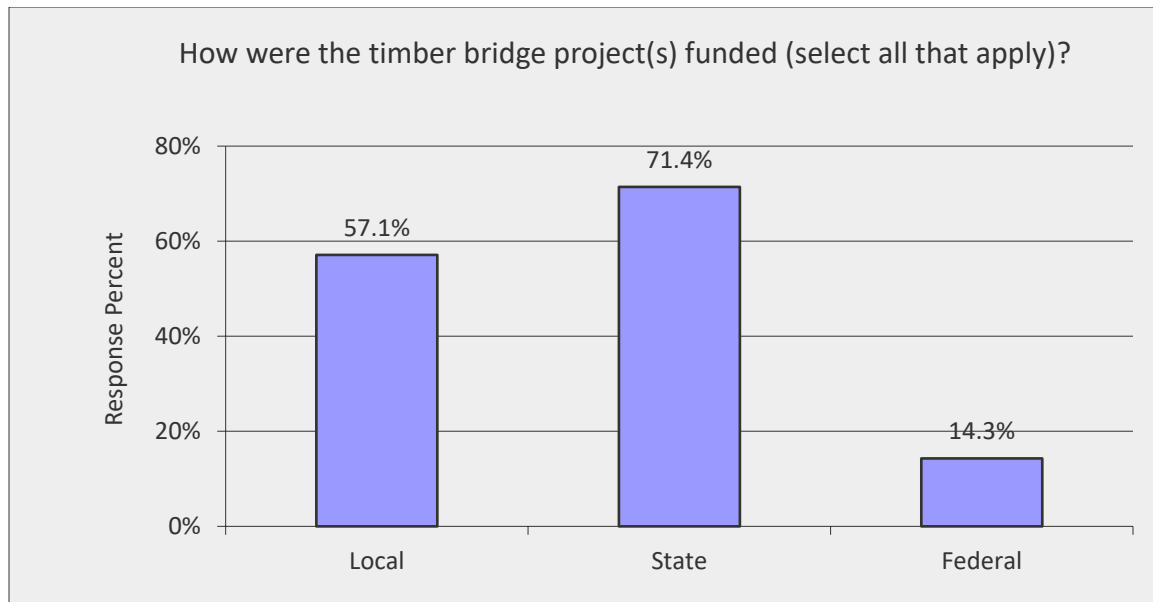


Figure 2.6 Responses showing how bridges constructed between 2005 and 2016 were funded.

Question 8: What other information or comments would/can you share regarding the decision making and construction of a new timber bridge?

There were 16 total responses, and a variety of answers were given. Some trends were that wood is great for aesthetics. Also, a common answer was that it is not cost efficient to use wood because the initial cost is more than concrete and there are more maintenance costs associated with wood. Lastly the comments seem to question wood's durability, longevity, and load capacity for high volume roads. The responses were:

1. Trail bridge. Used timber to minimize impact to surrounding area. Timber bridge is aesthetically pleasing
2. Too expensive in compared to longevity costs.
3. We do not normally choose this option.
4. In our area initial construction cost is nearly the sole consideration in structure choice. Timber costs would need to be competitive with concrete.
5. Selected timber for a natural look on a bridge leading to an island.
6. We only used timber rails on a recent bridge replacement for aesthetics.

7. We don't consider timber with the high traffic volumes we have. We've had some in the past and they are very high maintenance.
8. It was a very costly bridge. Only build because we received state park road account funding and it was in a park setting so aesthetics played a major role in deciding to go with a timber bridge.
9. We have a number of older timber bridges. We are having rotting problems with the timber pile in the water.
10. Public perception of treated material in or near water is big negative.
11. A timber bridge design meeting State Aid standard may be a nice alternative for low traffic roads.
12. Have NOT constructed on since 1998, when I started
13. Longevity of timber compared to concrete and steel
14. Last timber bridge built in 2001. I recall costs were approximately the same as simple span concrete/or series of precast concrete culverts.
15. Timber allowed us to phase the project allowing use of half the new bridge to maintain traffic.
16. Timber must be cost competitive.

Question 9: If you have not constructed a timber bridge since 2005, what are the biggest drawbacks or negatives to considering a timber bridge option for your county?

Figure 2.7 shows the results. The most popular answers were “Durability,” “Maintenance Costs,” and “Life-Cycle Cost” respectively. These results only further confirm that the greatest concern for most engineers participating in this study is the durability of wood, echoing the results of Question 8. Additionally, the participating engineers do not feel that the cost of maintenance on wood is not competitive with concrete.

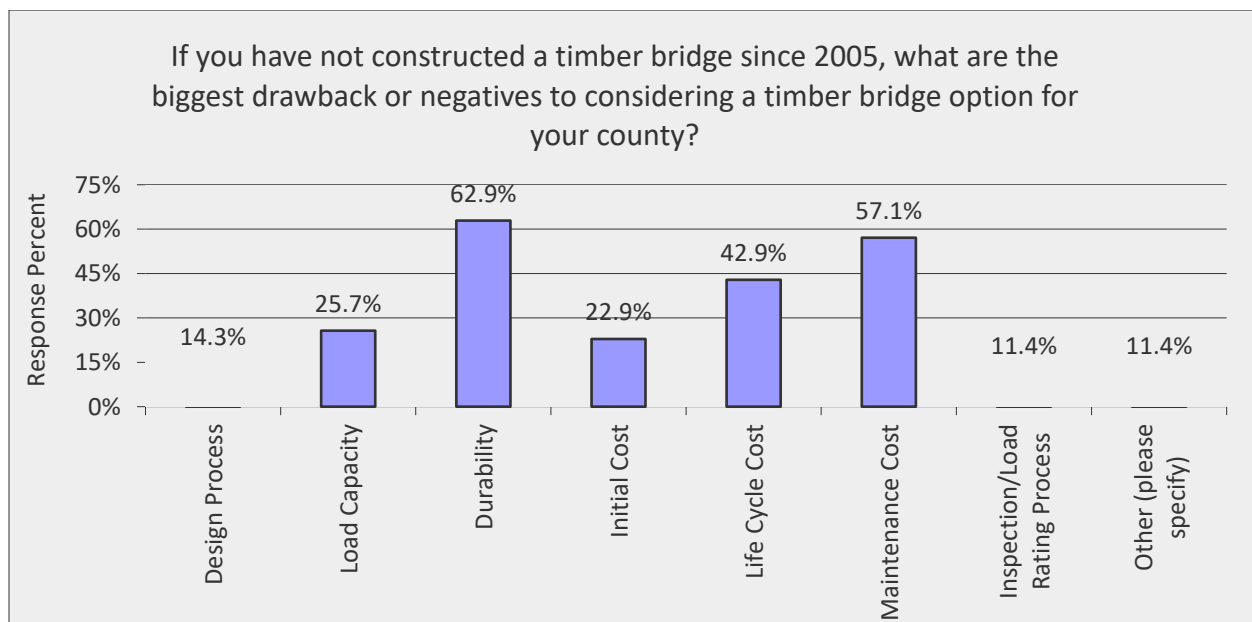


Figure 2.7 Responses to drawbacks or negatives to timber bridges.

Question 10: What suggestions do you have to reduce costs associated with timber bridge construction?

Participants were given two options for this question, “Design Process” or “Contracting or Build Strategies.” The responses on this question were dead even. Out of 19 engineers who answered this question, each option was chosen 12 times. This means that in the opinion this survey’s participants, if improvements to the cost of either of these processes are made, it could greatly help the overall cost of constructing timber bridges. Figure 2.8 shows the results.

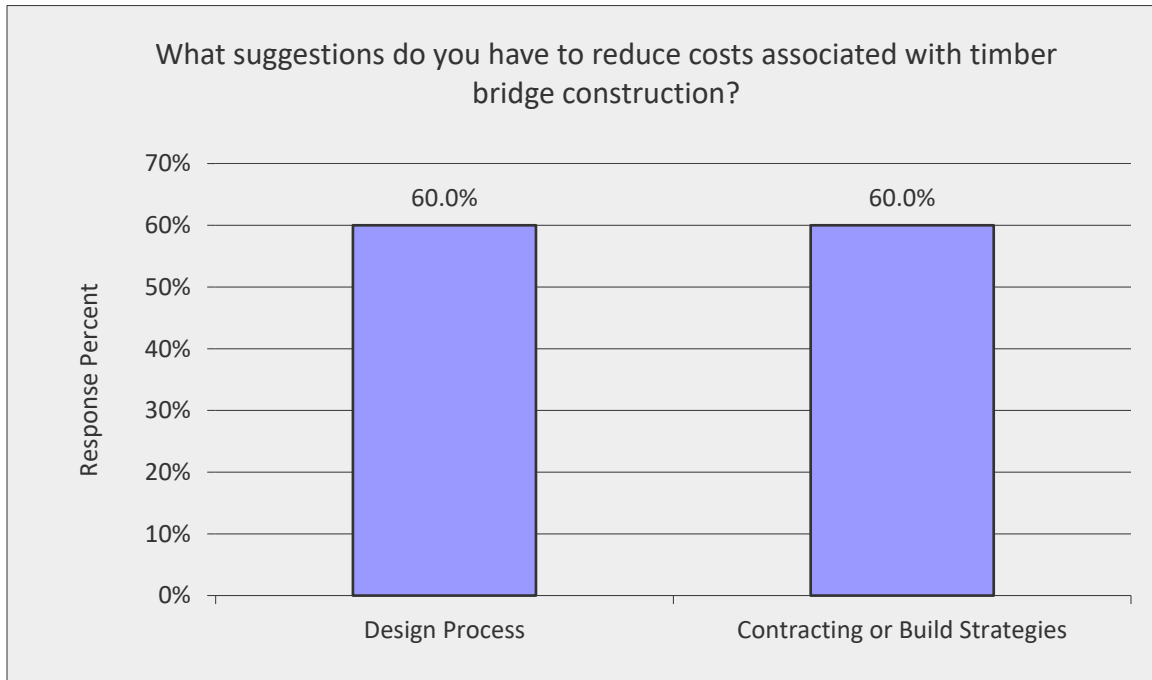


Figure 2.8 Potential timber bridge cost reduction options.

Question 11: Do you consider life-cycle cost analysis for new bridge construction projects?

Figure 2.9 shows the results of this question. “Always” and “Sometimes” were the most popular answers to this question. Each was selected 15 times out of 40 engineers who answered this question. “Never” was only selected by 10 of the participants.

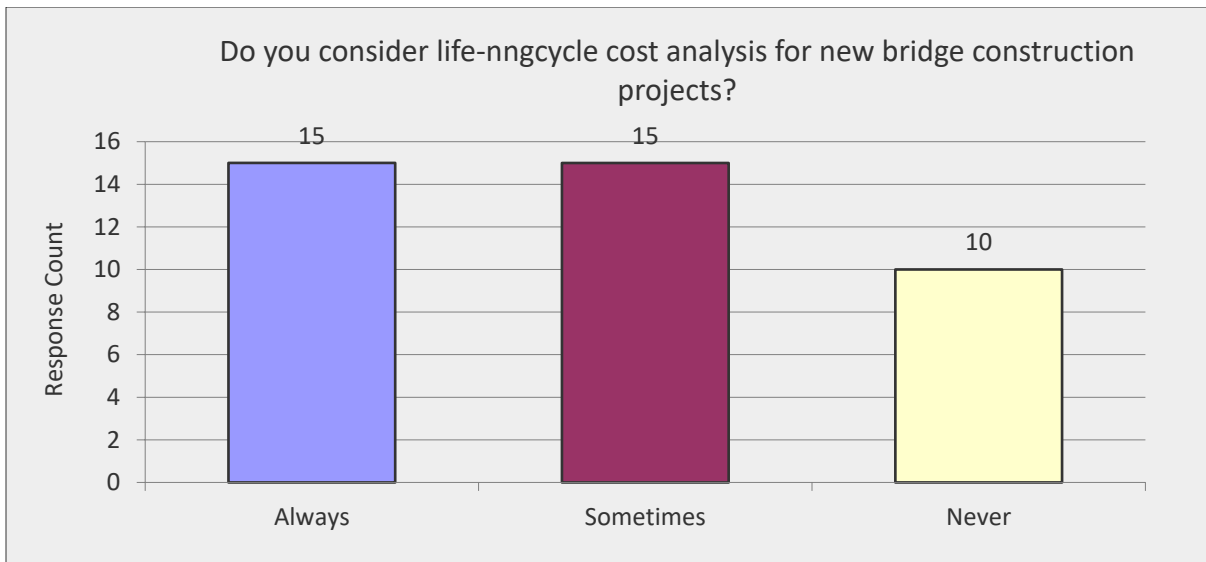


Figure 2.9 Response to the use of life-cycle analyses.

Question 12: Since you answered “Always” or “Sometimes” to the previous question, what factors do you consider in your life-cycle cost?

Although other answers were given, by far the most common responses for this question were as follows: initial cost, life-cycle cost/maintenance, durability, and expected service life of the material. The responses received were more typical for life-cycle cost analysis (LCCA) than life-cycle analysis (LCA) indicating a lack of familiarity with the environmental aspects of LCA. The responses were:

1. Bituminous overlay cost, railing and deck durability
2. Ability for maintenance crew to repair timber structures.
3. Life of bridge and maintenance
4. *In reality - If the initial costs of timber bridges vs concrete bridges are the same, I assume the life-cycle cost of the concrete bridge will be better than that of timber over the long term.
5. Life and maintenance costs
6. I expect to get 20 years more than a timber from a box culvert with no more cost to install.
7. Routine maintenance
8. Damage/debris maintenance
9. Anticipated Life
10. Initial Cost

11. Longevity, maintenance, reliability, construction cost
12. Repair, maintenance, design life
13. Initial cost, long term maintenance costs, detour length,
14. Initial cost, type of roadway, construction time
15. Cost over the life of the structure
16. Maintenance and how long it will last.
17. Expected maintenance and life based on previous experience
18. Initial cost, future maintenance cost, and routine inspection costs
19. Age before replacement
20. Deterioration of components
21. Maintenance effort and cost for the expected +75 year life of a bridge.
22. Material life
23. Construction cost and expected life span
24. Maintenance
25. In-house or contracted maintenance activities. Administrative and/or engineering costs of future inspections or maintenance projects. Construction cost inflation.
26. Long term maintenance costs.
27. Life span related to the bridge materials
28. For short spans the life cycle of precast concrete box culverts is our choice every time. They last forever and are quick to build.
29. Current and long term planning of the corridor; many of our sites will facilitate the extension of box culverts sections to allow widening.
30. Durability, routine maintenance, inspection frequency
31. Initial cost and life span of structure
32. Projected life of the replacement structure and initial cost.

Question 13: Do you feel that timber bridges are a more sustainable option as wood is considered a renewable resource, typically requires less energy to manufacture, and sequesters carbon?

Nearly 50% of the engineers in this survey responded with “No” while only 10.3% responded with “yes.” Figure 2.10 shows the results.

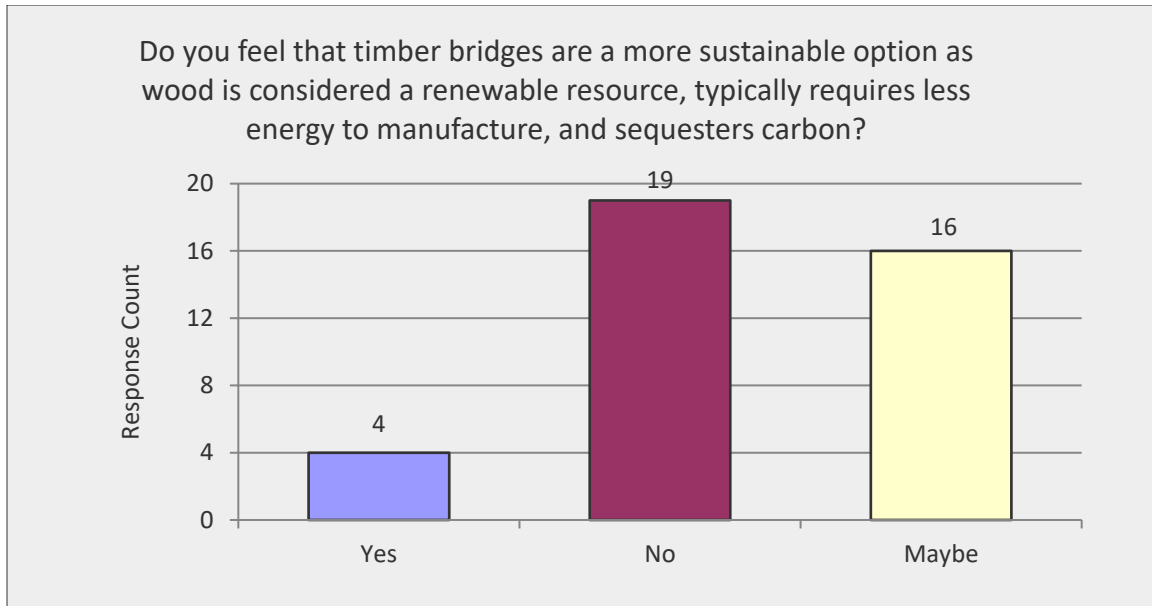


Figure 2.10 Responses that indicate whether they consider timber a more sustainable option.

Question 14: Do you factor environmental consideration for CO₂ emissions, or energy to manufacture into your bridge design and construction process?

Every engineer who answered this question responded with “no.” Figure 2.11 shows the results.

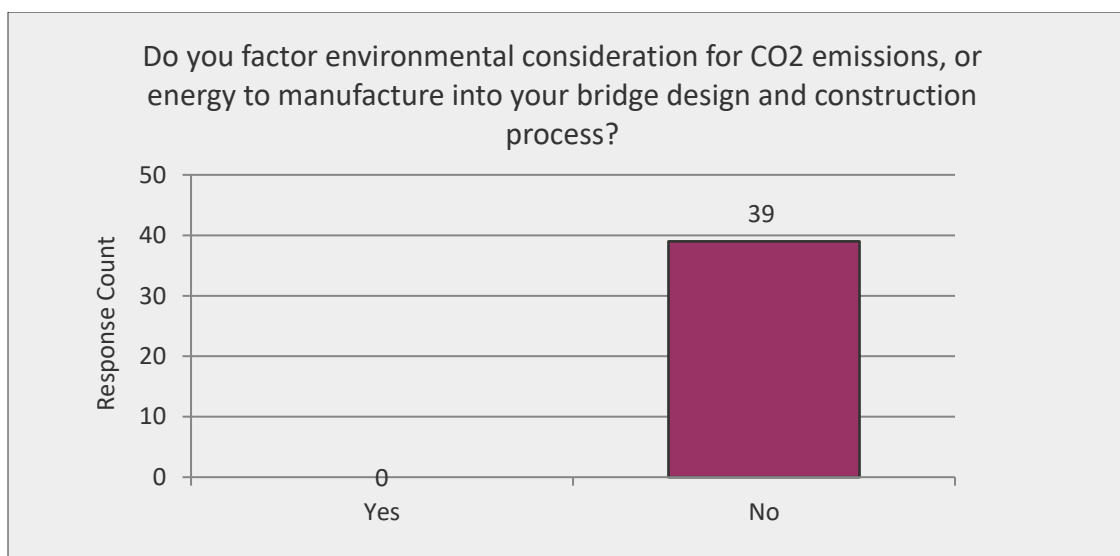


Figure 2.11 Responses on whether environment performance is considered during bridge design.

Question 15: How do you typically perform maintenance and repair of timber bridges?

The most popular response was “County Crew” with 88%. Approximately 48% responded with “Contractor.” This shows that both are used with some regularity and some engineers are not exclusive to one or the other. Figure 2.12 shows the results.

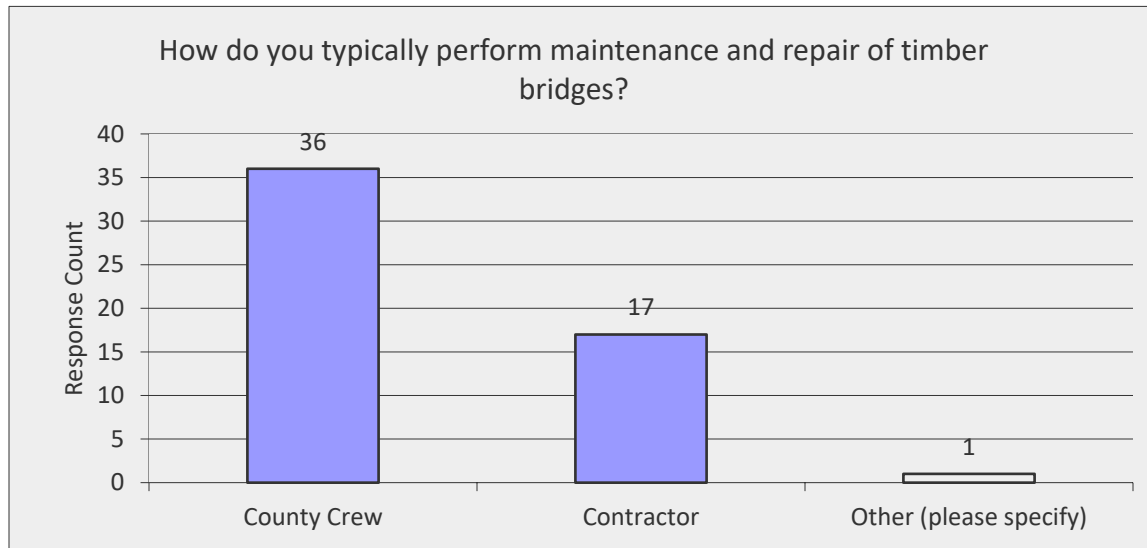


Figure 2.12 Response about who conducts ongoing bridge maintenance.

Question 16: How do you perform timber bridge inspections?

Most participants responded with “County Crew” with 91%. “Consultant” was chosen 21% of the time, showing that once again that there is some overlap where some engineers use both; however, county crews are used far more often in this case. Figure 2.13 shows the results.

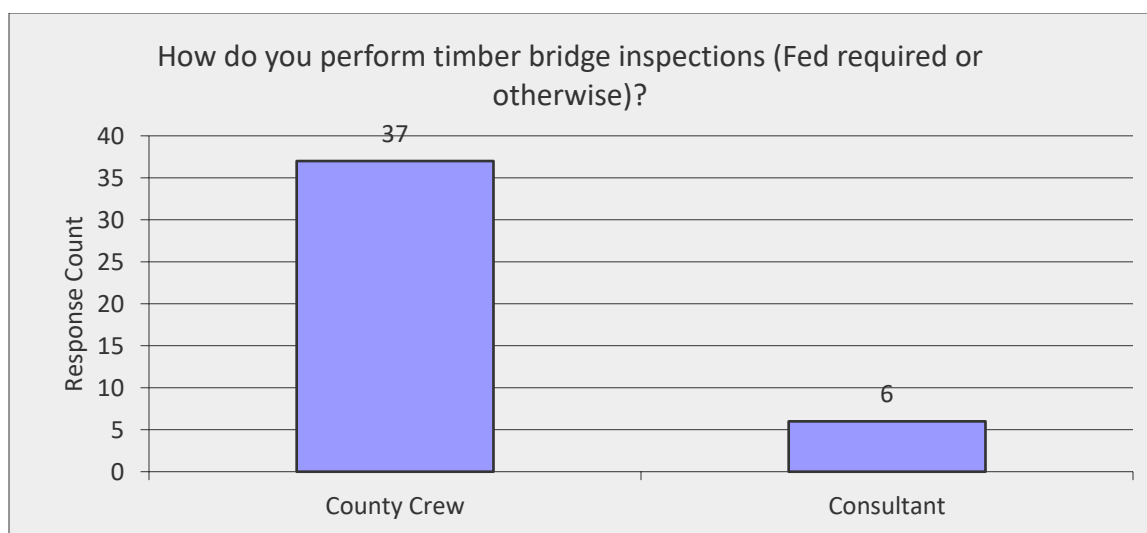


Figure 2.13 Response on who conducts ongoing bridge inspections.

The overall conclusions that can be drawn from this survey is that wood has a poor reputation among county engineers in the state of Minnesota. Concrete is by far the material of choice, as several engineers commented about how in their opinion, concrete was much better than wood. These engineers also questioned the longevity, durability, and cost of wood. Additionally, it can be concluded from this survey that many of the participating engineers are not familiar with modern timber bridge design as several comments noted that the last time that that specific engineer had worked with wood, or made a timber structure, was the late 1990s or earlier. It is also clear that there is a lack of understanding of LCA as compared to LCCA. Lastly it can be concluded that most of the maintenance and inspections are performed by the county crews. Coinciding with that fact, most of the funding for these timber bridge projects comes from the local and state levels.

2.1.5 Summary of MnDOT Cost Tables

An assessment of bridge construction costs was developed for the past five years (2011-2015) based on data provided by MnDOT State Aid office (MnDOT 2015). Table 2.1 shows the summary of costs for the following bridge types.

Table 2.1 Summary of bridge construction types and average costs for 2011-2019.

Bridge Type	Number of Bridges Constructed and Cost/Square Ft of Bridge Area								
	2019	2018	2017	2016	2015	2014	2013	2012	2011
Pre-Cast Beams (PCB)	16 \$161/ft ²	17 \$155/ft ²	29 \$136/ft ²	23 \$135/ft ²	21 \$152/ft ²	23 \$137/ft ²	28 \$130/ft ²	29 \$125/ft ²	41 \$119/ft ²
Concrete Slab Span (C-SLAB)	11 \$131/ft ²	21 \$133/ft ²	12 \$119/ft ²	17 \$136/ft ²	12 \$121/ft ²	11 \$123/ft ²	39 \$111/ft ²	24 \$113/ft ²	13 \$109/ft ²
Steel Beam (STEEL)		3 \$561/ft ²		1 \$230/ft ²	1 \$457/ft ²			1 \$611/ft ²	1 \$1,241/ft ²
Inverted T-Beams (INV-T)				1 \$284/ft ²	1 \$290/ft ²			2 \$213/ft ²	
Steel Truss (TRUSS)	1 \$274/ft ²	2 \$276/ft ²	1 \$216/ft ²	1 \$264/ft ²	6 \$294/ft ²	7 \$244/ft ²	2 \$323/ft ²	2 \$150/ft ²	2 \$192/ft ²
Glulam Bridge Beam (Glulam)									1 \$343/ft ²
Treated Timber Slab (TTS)	1 \$152/ft ²	2 \$216/ft ²		2 \$192/ft ²				1 \$222/ft ²	

CHAPTER 3: STANDARD SUPERSTRUCTURE OPTIONS

Based on the products from Task 1, standard superstructure options were developed for Minnesota with an emphasis on cost-competitive, long-lasting timber bridges with specific moisture management details. These designs included glulam beam with glulam deck, sawn timber spike-laminated panels and/or steel beam with timber deck. Design innovations and contracting options were explored to support reduced cost options.

3.1 STANDARD SUPERSTRUCTURE DESIGN AIDS

Based on the results of background material assessments highlighted in chapter 2, standard superstructure design aids were developed for three type of superstructure designs. These included:

1. Steel Stringers with a Transverse Glulam Deck
2. Glulam Stringer with a Transverse Glulam Deck
3. Longitudinal Spike-Laminated Timber Deck

The focus of this project was to develop standardized timber bridge design aids and specifications for Minnesota. These standard plan aids and specifications should assist engineers who are not familiar with timber design. The information provided in this report was developed as a cooperative effort with the Minnesota Department of Transportation, US Forest Service, Forest Products Laboratory, and the University of Minnesota Duluth with additional engagement from Wheeler Consolidated/Erickson Engineering, Laminated Concepts, Inc., and LHB Inc. Every effort has been made to present the information in a user-friendly format and allow maximum flexibility for the use of different wood materials, species, and grades. Each set of plans encompasses a basic span length and width combination, based on AASHTO LRFD Bridge Design Specifications for Highway Bridges, 5th Edition (2017). The information is intended to augment or support design requirements by the owning agency. In all cases, the design information must be verified by a Minnesota Registered Professional Engineer experienced with timber bridge design prior to plan development and construction. The Minnesota Department of Transportation, University of Minnesota Duluth and the US Forest Service hereby give notice that the information contained shall not create any warranty expressed or implied.

An example set of timber bridge construction plans and documents will be provided based on actual construction of timber bridges during Task 3A and 3B of this project or from recently constructed timber bridges in Minnesota or Iowa. These examples would provide meaningful background and information for county engineers and others that may not have significant experience with timber bridge design and construction. Each example will have detailed photographs and other documentation of the cost-effective and durable construction design details. They will include:

1. Transverse glulam deck steel beam bridge southeast of Babbitt, in St. Louis County, Minnesota. This is state bridge number 69A58 also referred to as county bridge number 516.
2. Spike-laminated longitudinal deck bridge that was constructed in Hennepin County. This is State Aid Bridge L8081 which is replaced now with 27C53.

3. Glulam stringer and transverse glulam deck (*superstructure type not built within this project*).

The Standard Design Aids are attached to this report as Appendix A, B, and C.

3.1.1 Steel Stringers with a Transverse Glulam Deck (Appendix A)

- Perspective Drawing & Photographic View
- Design Information – Glulam Deck System
 - Transverse Cross-Section Views
 - Design Notes
- Glulam Panel-to-Stringer Connections – Key Design Details
- Design Information – Steel Girders
 - Transverse Cross-Section Views
 - Design Notes
- Steel Girder Details
 - Diaphragm Configuration
 - Abutment Bearing Connections
- Crash-Tested Bridge Railing Options
 - NCHRP-350 TL-2 Glulam Railing System (without Curb)
 - NCHRP-350 TL-4 Glulam Railing System (with Curb)
- Wearing Surface and Durability Details

3.1.2 Glulam Stringer with a Transverse Glulam Deck (Appendix B)

- Perspective Drawing and Photographic View
- Design Information – Glulam Stringers
 - Cross-Section Views
 - Design Tables with Girder Sizes
 - General Notes
- Diaphragm and Stiffener Beam Details
- Glulam Deck Panel-to-Stringer Connections
- Substructure Connection Details – Concrete, Steel, and Timber Abutment
- Crash-Tested Bridge Railing Options
 - NCHRP-350 TL-4 Glulam Railing System with Curb
 - Asphalt wearing surface and waterproof membrane placement

3.1.3 Spike-Laminated Longitudinal Deck (Appendix C)

- Perspective Drawing Photographic View
- Plan & Profile Views and General Notes
 - Deck Design Maximum Span Table
- Configuration of Deck Panels
 - Cross-Section View – Layout of Panel Splices
 - Cross Section View – Stiffener Beam
 - Timber Pile Abutment Attachment Detail
- Deck Panel Configuration and Crash-Tested Bridge Railing
 - Spike Lamination Prefabrication Details
 - NCHRP-350 TL-4 Glulam Railing System with Curb

- Abutment Bearing and Drainage Details
 - Timber Pile Cap Attachment – Cross-Section View
 - Timber Pile Cap Attachment – Side View
 - Asphalt wearing surface and waterproof membrane placement
 - Metal Flashing Details
 - Inside Curbs
 - Inside Scupper Block Openings

3.2 COST-EFFICIENT DESIGN AND CONSTRUCTION CONSIDERATIONS

Timber bridge construction offers the potential for cost-efficient construction; however, the lack of current timber bridge construction has not offered significant competition or clear cost advantages. However, this project is working to identify cost saving strategies in design and construction, that when paired with improved durability details, will create options for cost-effective timber bridges with a service life of 70+ years. This includes activities including preservative selection, contracting and construction options, bridge design, fabrication, construction/installation, and design innovations to minimize long-term maintenance. Each of the following sections will provide more information.

3.2.1 Preservative Treated Wood Waiver Process

One of the challenges noted by one of the bridge component producers and suppliers in Minnesota was that the current MnDOT preservative use guidelines ([MnDOT Approved/Qualified Products Treated Wood](#)) specifically do not allow for the use of copper naphthenate. However, each local bridge owner can work with MnDOT to gain approval for components including copper naphthenate. To simplify and reduce this identified barrier, the State Aid Bridge Office, under advisement from the MnDOT Office of Environmental Stewardship and significant assistance, input and vetting from the timber industry, has developed a treated wood waiver letter for local agencies to use as a template on projects that contain treated wood, and where they wish to waive the use restrictions set forth in MnDOT's approved preservatives for the treatment of timber products. The Treated Wood Template Waiver forms will allow timber bridge owners to use a wider variety of preservative treatments that have been adopted by both the AASHTO and EPA for their project application. It gives the local owner the ability to consider factors such as environmental risk, cost, and durability in their final selection of wood preservatives, all with the understanding they can discuss the potential environmental liability associated with their selection of wood preservative with the MnDOT Office of Environmental Stewardship at any time. Complete information on this process, including access to a waiver letter, are available at: <http://www.dot.state.mn.us/stateaid/bridge/wood-treatment.html>.

3.2.2 Contracting and Construction

The literature review completed in Task 1 and interviews with bridge construction projects clearly shows that timber bridges can be constructed year-round, depending on the substructure selected for the project. This offers the potential for winter construction projects when bridge construction companies typically have fewer active projects. However, feedback has also been provided that many construction companies in northern Minnesota may not choose to actively bid on timber bridge construction projects during the winter. Figure 3.1 shows an actual winter construction project using a longitudinal spike-laminated timber deck.



Figure 3.1 Winter construction of a longitudinal spike-laminated timber deck.

3.2.3 Accelerated Bridge Construction

It is also clear from a wide range of timber projects that timber bridge construction projects can significantly reduce the construction duration and the length of time associated with bridge closures, or detours. This offers a unique opportunity for various timber bridge construction options. This could include either steel or glulam stringers, combined with transverse glue laminated deck systems, or a longitudinal spike laminated timber deck. These materials can be successfully used to construct projects in as few as 14 days (Hemmila, 2017). A 2014 project completed by St. Louis County replaced a high ADT bridge by using steel beams and a transverse timber deck in only 14 days, which included deconstruction. User cost savings associated with lengthy detours or other considerations make timber bridges an effective option. This has been documented through the literature review conducted during Task 1 and recent timber bridge construction projects that have occurred in St. Louis County, various Wisconsin counties, and in Iowa. Actual time associated with demonstration construction projects in Task 3 will be tracked.

3.2.4 Spike-laminated Timber Bridge Specific Considerations

Wheeler Consolidated is currently exploring the option to reduce the AASHTO-LRFD strength reductions associated with incising (i.e., small perforations in the wood surface to increase preservative penetration) on Douglas fir dimension lumber used in construction. Any lowering of the incising reduction would have a positive impact on the strength and stiffness increases of the material, resulting in potential span or load increases, which would have a positive impact on the cost-effectiveness of this bridge technique.

Further, Wheeler Consolidated is exploring the issues and design considerations of having a TL-2 crash-tested railing system for a nail-laminated transverse timber deck that could be used on steel or glulam girders. This could have a positive impact on the cost-effectiveness of this timber component.

3.2.5 Multiple presence factors

Timber bridges are typically on low volume roadways e.g. ADTT<100, hence per AASHTO Commentary, a 10% reduction in the multiple presence factors can be considered. This could potentially decrease the material costs/linear foot and improve the cost-effectiveness of a timber bridge system. In bridge design the multiple presence factor addresses the probability of multiple fully loaded lanes occurring simultaneously. The multiple presence factor goes down as more lane loads are considered.

3.2.5.1 Multiple Presence of Live Load (From AASHTO LRFD Bridge Design Specifications, Seventh Edition, 2014)

Table 3.1 Multiple Presence Factors, *m*

Number of Loaded Lanes	Multiple Presence Factors, <i>m</i>
1	1.20
2	1.00
3	0.85
>3	0.65

3.2.5.2 Multiple Presence of Live Load Commentary

The multiple presence factors in Table 3.1 were developed based on an ADTT of 5,000 trucks in one direction. The force effect resulting from the appropriate number of lanes may be reduced for sites with lower ADTT as follows:

- If $100 \leq \text{ADTT} \leq 1,000$, 95 percent of the specified force effect may be used; and
- If $\text{ADTT} < 100$, 90 percent of the specified force effect may be used.

3.2.6 Contractor Supplied Designs

The potential exists for contractors to supply designs at no-additional-cost for timber bridge construction projects and may offer the potential to reduce costs associated with bridge designs. One example of this approach is the MnDOT Technical memorandum No. 16-02-B-01 for the use of three-sided precast concrete bridge structures. It is available at <http://dotapp7.dot.state.mn.us/edms/download?docId=1694678>. This document provides design and construction guidelines and a preliminary construction data sheet.

3.2.7 Geosynthetic Reinforced Soil Abutment Considerations

Options for low-cost abutments on low-volume roads, and specifically timber bridge superstructures, exist that assist with meeting cost needs, to reduce construction time, and to improve ease of construction. Actual dollar numbers aren't currently available (but have been requested) for the alternatives discussed below. However, to simply evaluate the alternative solely on upfront material cost would be a mistake. Reduced construction time, required skilled labor, need for heavy equipment, and service life are all factors that should be put into any cost analysis. It should be noted however, that abutment costs are largely dependent on local site conditions, bridge design requirements and several other factors. Context is important to ensure that valid comparisons are made. Further, often the best and most economical abutment alternative may depend on the availability of equipment to whomever is constructing the abutment (county, contractor, etc.) in addition to actual material costs.

Geosynthetic reinforced soil (GRS) abutments are a potential cost-effective option with increasing popularity. Specific details, resources, design drawings, and other reference material for GRS abutments can be found at: <https://www.fhwa.dot.gov/innovation/everydaycounts/edc-3/grs-ibs.cfm>.

This abutment option involves building up the abutment using alternating layers of compacted granular material and geotextile fabric in 6- to 8-in lifts. Once the GRS is constructed to the desired and required elevation, abutment caps (these may be concrete, timber, etc.) are placed directly on top of the GRS layer. Then girders and back wall are installed, and layers of GRS are added until a grade elevation just below roadway paving is achieved. In certain situations, the beams may also be set directly on the GRS abutment with no cap beam installed. Currently, two facing options exist to tie-in the vertical face under the bridge and protect the GRS from water damage in the case of a stream/river crossing: 1) CMU block, and 2) sheet pile. Pros and cons exist for both facing options, but in general the Federal Highway Administration (FHWA) notes construction cost savings of 25-60% when using GRS vs traditional foundation options.

Two projects completed in Iowa on secondary roads have shown that, using county personnel, both bridge abutments can be constructed in less than two working days. The only equipment outside of a small backhoe required was a small crane to shake the sheet pile into the ground. In areas of scour concern, use of the sheet pile facing and driving them to below scour depth exhibit significant potential for future cost/maintenance savings. Additional information on GRS abutments is in an internal Forest Service report by Brian Keierleber (2017). Figure 3.2 shows a typical GRS abutment. Figures 3.3 and 3.4 show recent pictures from a project that was completed in 2016 in northern Iowa.

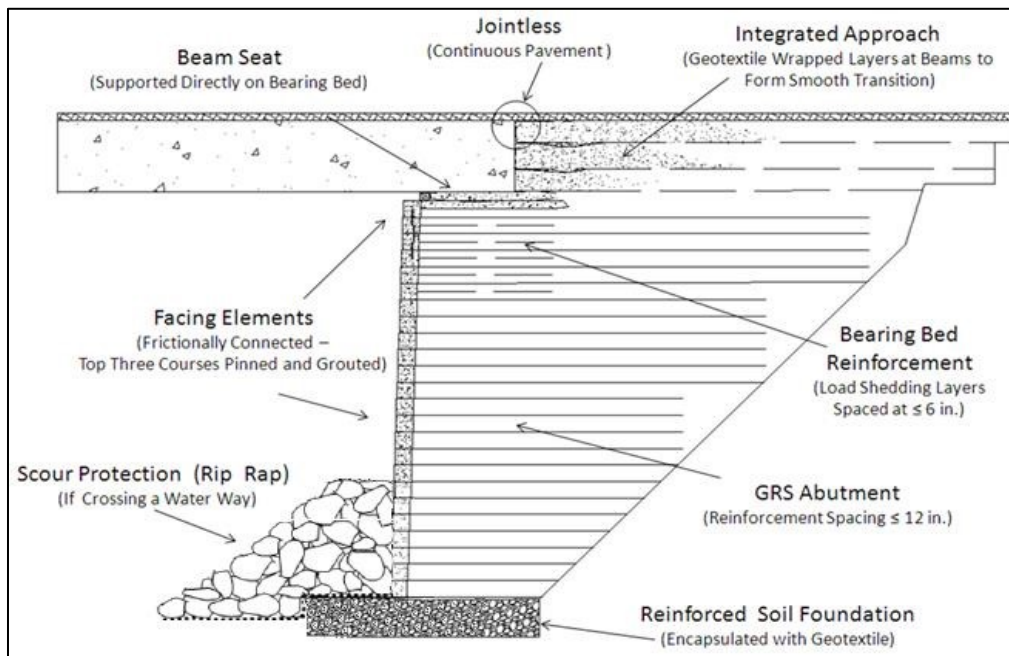


Figure 3.2 Typical geosynthetic reinforced (GRS) abutment elements.



Figure 3.3 GRS abutment during construction in Buchanan County, Iowa (2016).



Figure 3.4 GRS abutment construction and bridge deck installation in Buchanan County, Iowa.

3.2.8 Sheet Pile Abutment

Sheet pile abutments have been utilized in several counties in Iowa (Evens, 2010), as well as in Minnesota, with immediate results indicating that there is potential for this alternative to be viable on low volume roads, but numerous factors come into play when determining if they are economically viable. An experimental project was completed in Iowa in 2010 that showed the positive potential for using sheet. Factors include but are not limited to depth to bedrock, or lack thereof; length required to meet bearing needs; need for and cost of dead men for lateral stability; others.

3.2.9 Local Species and Fiber-reinforced Structural Materials

Research and demonstration bridge projects to further develop wood for transportation structures increased substantially in the United States in 1988 under a legislative action by the US Congress known as the Timber Bridge Initiative. The program was renamed the Wood in Transportation Program (Duwadi, 2000) and functioned through 2005. Significant work was accomplished to construct bridges from local wood species, usually on secondary and local US road systems. Most of the timber bridges were short-span structures. They included traditional construction using sawn timber beams and nail-laminated bridges, but most were newer designs such as glued laminated timber bridges, stress-laminated bridges, dowel-laminated bridges, glued-laminated timber arches, and other state-of-the-art engineered wood bridges such as timber bridges reinforced with fiber-reinforced polymer (FRP) composites (Figure 3.4) and structural composite lumber. Several of these projects looked at the use of wood species native to Minnesota, including red pine, red maple, jack pine, and cottonwood. However, it was noted that these species require challenges associated with lack of structural size, lack of grade required for use in timber bridges and lack of availability. While cost studies were not a specific focus of the projects, it was noted that they were not initially cost-competitive but might create local market options for these species.

3.2.10 Crash-Tested Railing System for Timber Bridges

Federal Highway Administration approved crash-tested railing systems for timber bridges are located at: https://safety.fhwa.dot.gov/roadway_dept/countermeasures/reduce_crash_severity/listing.cfm?code=I [ong](#). Table 3.2 shows an overview of the crash-tested rating system for AASHTO, NCHRP 350, and MASH. MnDOT currently recognizes NCHRP-350 TL2 and TL4 systems until MASH-approved bridge railing systems become available. Table 3.3 provides an overview of the crash-tested systems by bridge type.

A variety of bridge railing systems have had full-scale crash-tests performed on wood recently and are now approved for use on highway bridges. Many of these efforts resulted from a collaboration between the Midwest Roadside Safety Facility (University of Nebraska-Lincoln) and the Forest Products Laboratory (USDA Forest Service). See Appendix C-2 for an overview of the research program. Another resource for information on crash-tested systems is: Crash-Tested Curb-Railing Systems for Low-Volume Road Applications, [FPL-GTR-107](#).

Table 3.2 Summary of crash-testing criteria by AASHTO, NCHRP, and MASH requirements.

AASHTO Performance Level ⁽¹⁾	Impact Conditions		
	<i>Small car</i> (816 kg, 1,800 lb.)	<i>Pickup truck</i> (2,449 kg, 5,400 lb.)	<i>Medium Single-unit truck</i> (8,165 kg, 18,000 lb.)
1	80.5 km/hr (50 mph) 20 degrees	72.4 km/hr (45 mph) 20 degrees	--
2	96.6 km/hr (60 mph) 20 degrees	96.6 km/hr (60 mph) 20 degrees	80 km/hr (50 mph) 15 degrees
NCHRP 350 Test Level ⁽²⁾	Impact Conditions		
	<i>Small car</i> (820 kg, 1,808 lb.)	<i>Pickup truck</i> (2,000 kg, 4,409 lb.)	<i>Medium Single-unit truck</i> (8,000 kg, 17,637 lb.)
1	50 km/hr (31 mph) 20 degrees	50 km/hr (31 mph) 25 degrees	--
2	70 km/hr (43 mph) 20 degrees	70 km/hr (43 mph) 25 degrees	--
4	100 km/hr (62 mph) 20 degrees	100 km/hr (62 mph) 25 degrees	80 km/hr (50 mph) 15 degrees
MASH Test Level ⁽³⁾	Impact Conditions		
	<i>Small car</i> (1,016 kg, 2,420 lb.)	<i>Pickup truck</i> (2,270 kg, 5,000 lb.)	<i>Medium Single-unit truck</i> (10,000 kg, 22,046 lb.)
1	50 km/hr (31 mph) 25 degrees	50 km/hr (31 mph) 25 degrees	--
2	70 km/hr (45 mph) 25 degrees	70 km/hr (44 mph) 25 degrees	--
4	100 km/hr (62 mph) 20 degrees	100 km/hr (62 mph) 25 degrees	90 km/hr (56 mph) 15 degrees

¹Michie, J. D. **NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances**. TRB, National Research Council, Washington, D.C., 1981.

²Ross, H. E., D. L. Sicking, R. A. Zimmer, and J. D. Michie. **NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features**. TRB, National Research Council, Washington, D.C., 1993.

³**Manual for Assessing Safety Hardware**. AASHTO, Washington, D.C., 2016.

Table 3.3 Overview of crash-tested railing overview by deck type.

Deck Type	Testing Protocol	Test Level 1	Test Level 2	Test Level 4
Timber Slab or Longitudinal Deck (spike-laminated, longitudinal glulam, or stress-laminated)	NCHRP Report 230 ¹ and NCHRP Report 350 ²	Curb Rail System TRR 1419	Glulam Rail with Curb System Glulam Rail <u>without</u> Curb System FPL-GTR-94 Link	Glulam Rail with Curb System FPL-GTR-94 Link TRR1500
Transverse Deck (nail-laminated)	MASH ³	Timber Curb System TRR 2262	Steel Railing System TRR 2262	
Transverse Deck (Glulam)	NCHRP Report 350		Includes both Glulam and Steel Railing Systems TRR 1743	Includes both Glulam or Steel Railing Systems TRR 1696
Concrete Deck	NCHRP Report 350	Curb Rail System	Glulam Rail Curbless System	Glulam Rail with Curb System

CHAPTER 4: ST. LOUIS COUNTY TIMBER BRIDGE CONSTRUCTION PROJECT

One of the project goals was to identify several bridge construction projects with partner counties that would use the developed plans, allowing the project team to assess and validate the true initial costs of construction, predict life-cycle costs, and complete a life-cycle assessment for these bridges. Potential MnDOT and county partners were identified for planning and construction of one beam and one slab type bridges. This chapter highlights the work conducted in Task 3A, where the project team partnered with St. Louis County, Minnesota on the design, construction and validation of a bridge that was constructed between Embarrass and Babbitt, Minnesota. This bridge was constructed by St. Louis County construction crews using steel girders and a transverse glue-laminated (glulam) deck. The team worked with St. Louis County to track design, bidding, cost-tracking and construction of the bridge. Funds from the project were not used for construction.

4.1 BACKGROUND

The St. Louis County Bridge selected for this project is state bridge number 69A58 and county bridge number 516 (referred to as SLC 516). It is located approximately 7.4 miles W/SW of Babbitt, MN and crosses the Embarrass River. It is located on CR 796. It is a low volume road with average daily traffic of <10 vehicles. The original bridge, a steel pony-truss bridge, was constructed in 1919 and had a cast-in-place concrete deck at the time of removal. Figures 4.1 and 4.2 show the bridge prior to removal. Figure 4.3 shows the location of the bridge.

Funding for the construction of the project was provided by St. Louis County, Minnesota. The site work and construction were completed by construction crews from St. Louis County. The project team included St. Louis County, University of Minnesota Duluth Natural Resources Research Institute, US Forest Service Forest Products Laboratory, LHB Engineering, Laminated Concepts Inc., and Iowa State University.



Figure 4.1 Original 1919 steel pony-truss bridge that was replaced during this project.



Figure 4.2 Embarrass River flowing under St. Louis County Bridge 516.

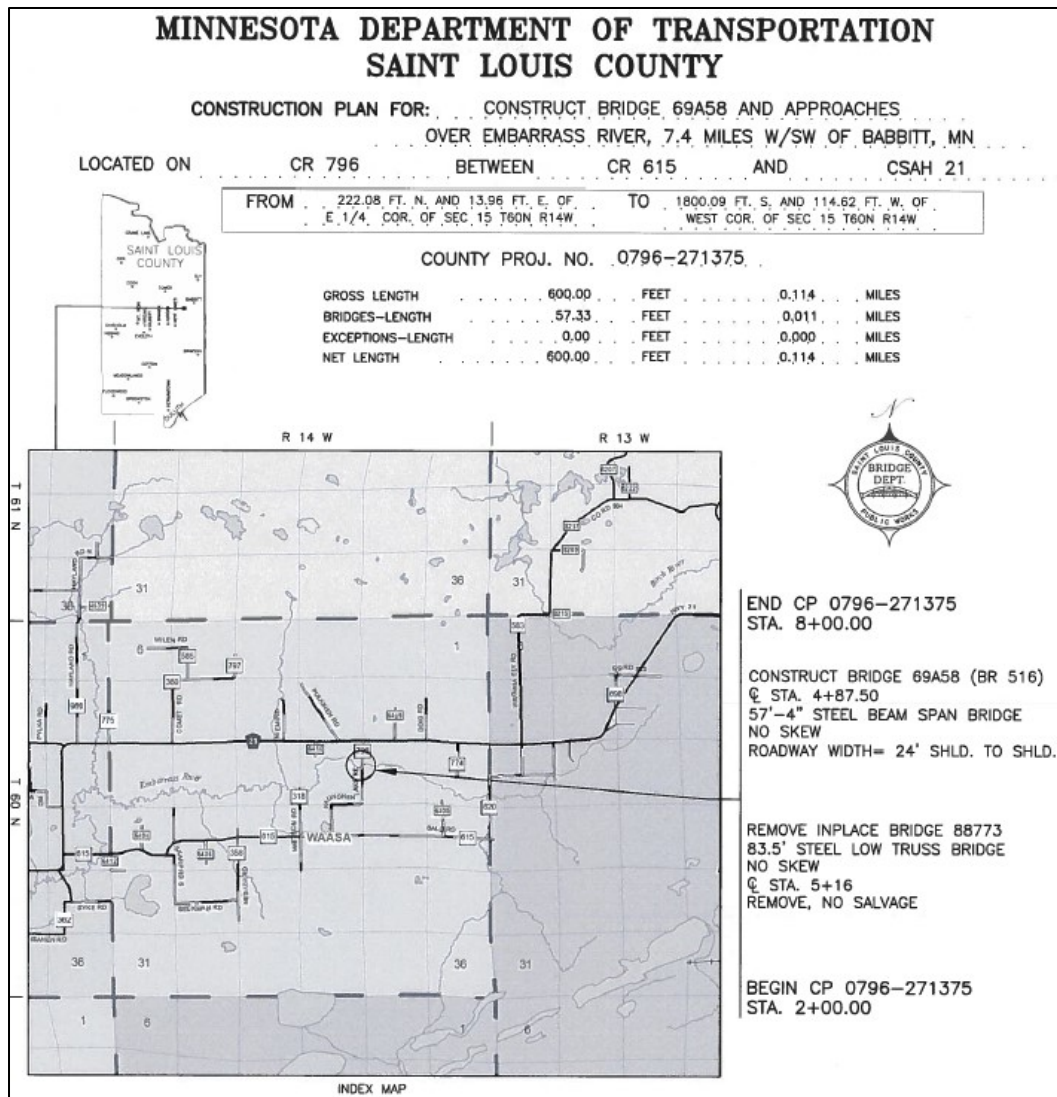


Figure 4.3 Geographic information and location of the project bridge.

4.2 OBJECTIVE AND SCOPE

The objective of this task was to identify, design and construct a demonstration bridge using standard timber design options and to develop and incorporate design details focused on long-term performance and durability. The focus would be on using a girder style bridge design using steel girders and a transverse glulam deck capable of being installed in a short time period. On-site photo and time documentation were also completed for the construction. The project team interfaced with the bridge owner, St. Louis County, and other partners to demonstrate and validate the cost parameters associated with the project and compare them to preconstruction estimates. A final life-cycle cost assessment and a life-cycle analysis was completed based on the specific bridge constructed. Funding and completion of the actual bridge construction were outside the scope of the requested project funds.

4.2.1 Design, Bid and Construction

The design and construction of SLC bridge 516 involved efforts from several agencies and organizations. An overview of the design, bid process, and construction of the bridge follows.

4.2.1.1 Design

The overall project design and site plan, developed by St. Louis County Public Works Department (MN), is in Appendix D. This includes the title sheet, and index map, statement of estimated quantities, earthwork quantities, typical section, plan and profile, bridge approach treatment, sheet pile wall, reason control plan, guardrail, traffic control, and bridge plan. The design of the steel girders was completed by St. Louis County with support from LHB Engineering. The design of the glulam deck panels and guardrail posts and rails for the project were completed by Laminated Concepts, Inc. Both design efforts were conducted in cooperation with St. Louis County to ensure that the superstructure and substructure designs were compatible.

The structural design for the bridge was done in accordance with the American Association of State Highway and Transportation Officials (AASHTO), LRFD Bridge Design Specifications for Highway Bridges (2017). The bridge design was comprised of a steel stringer system supporting a transverse glulam deck system and was designed for the design criteria:

- Dead load (timber 50 pounds per cubic foot (PCF) / wearing surface 140 PCF)
- Live load HL-93
- Live load deflection limit ($L/425$)

The design specified the following for the bridge, materials and fabrication:

1. The material and installation procedures should conform to the American National Standard for Wood Products – Structural Glued Laminated Timber ANSI A190-1 (latest edition), AITC 117-2015 Standard Specification for Structural Glued Laminated Timber of Softwood Species, AWWA Book of standards (latest edition), and the WWPI Best Management Practices for Treating Wood in Aquatic Environment.
2. The glulam manufacturer needs to be a qualified licensee of the American Institute of timber construction (AITC) or the APA–The Engineered Wood Association (APA/EWS). It was noted in design documents that all glue-laminated timber shall be factory fabricated (as far as practical). This included all cutting, drilling and other fabrication as shown on in the shop drawings. The laminator shall provide an AITC or APA/EWS Certificate of Conformance to AITC/ANSI A190.1-2007.
3. The lumber-intended for glulam production shall be visually or mechanically graded in conformance with accepted standards for LRFD unit stresses (See AASHTO Section 8) and with the National Design Specifications for Wood Construction. Glulam members shall be finished to Industrial Appearance Grade as per AITC 110-2001. All lumber utilized in these standards shall be either Coastal Douglas Fir or Southern Pine.

4. All timber should be treated with the following oil type preservatives in accordance with AASHTO Material Standards, M133 and M168 and shall conform to the AWPAs Use Code Standards 8.1 Pentachlorophenol or Copper Naphthenate in Type A, heavy oil conforming to AWPAs Standard UC4B, P-8 & P9. The retention level shall be 0.6 PCF. All preservative treatments shall be applied in accordance with Best Management Practices for Wood Preservatives in Aquatic Environments. Preservative treatment certification required. A Certificate of treatment shall be furnished by a certified AWPAs treating facility. The treating certification shall list the identification of job, species of materials, type and retention preservative provided, as well as the AWPAs standard used as the guide for treating. In the event treated glulam originates from more than one treating facility, then separate certifications shall be furnished from each facility providing timber for this project.
5. Fabricator shall provide all connection steel and hardware for joining wood members to each other and to their supports exclusive of anchoring embedded in concrete. All fasteners, except prestressing bars, shall be galvanized (ASTM A-123) mild steel ASTM A307. Washers to be cast iron or malleable iron, timber type. All steel plates and shapes to be galvanized (ASTM A-153) mild steel ASTM A-36.

Figure 4.4 shows the perspective drawing of the bridge superstructure design. The design features steel girders with diaphragms (Figures 4.4 and 4.5) with transverse glulam deck, longitudinal deck stiffeners, and the guard rail system (Figures 4.6, 4.7, 4.8, and 4.9). Drawings of galvanized flashing to protect the deck panel edges and rail posts from moisture related deterioration are shown in Figures 4.10 and 4.11.

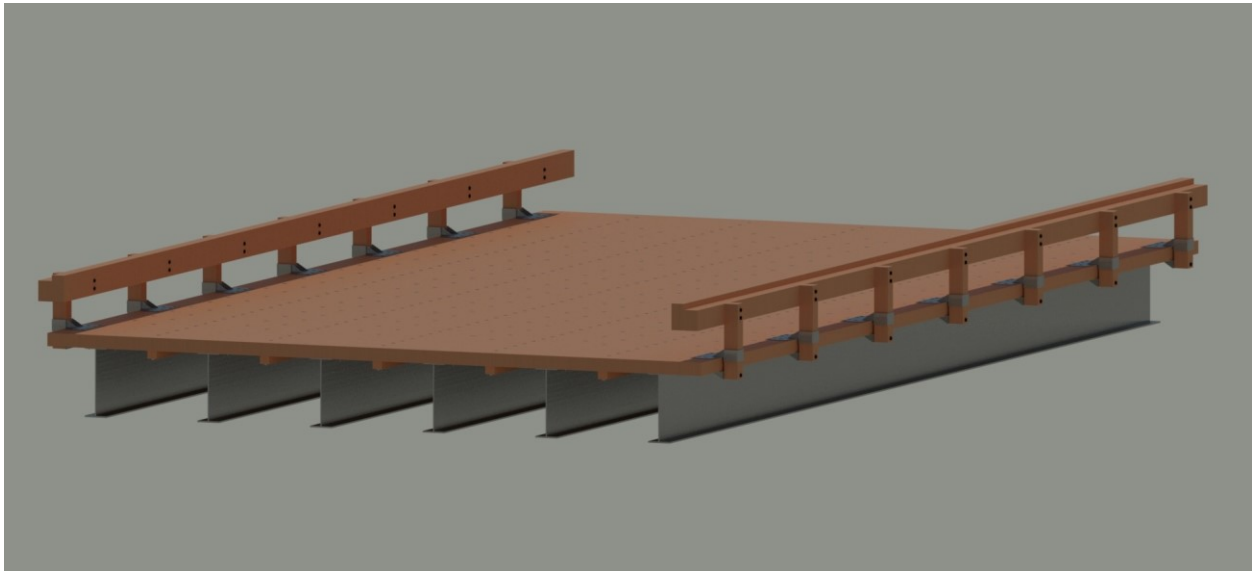


Figure 4.4 Perspective drawing of steel girder with transverse glulam timber deck, stiffeners, and railings.

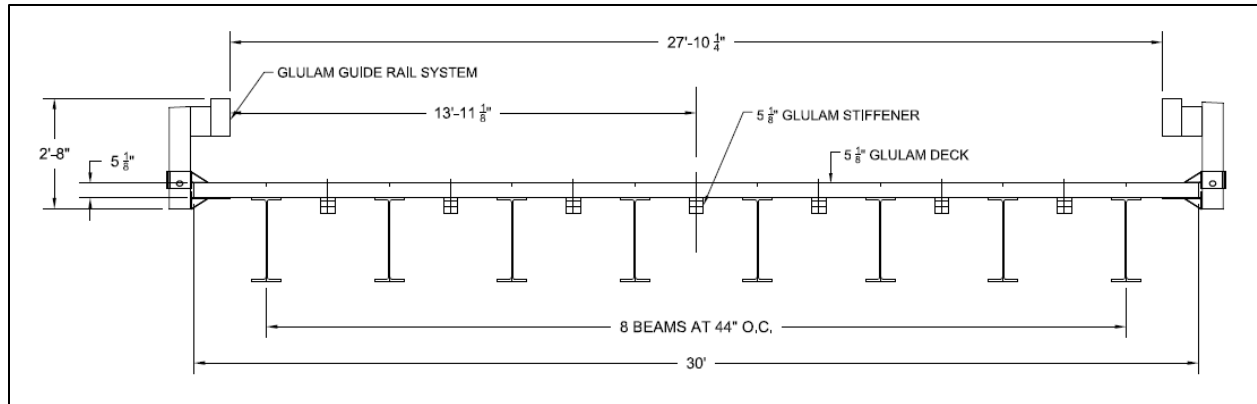


Figure 4.5 Cross-section view showing bridge steel girders, glulam deck, and stiffeners.

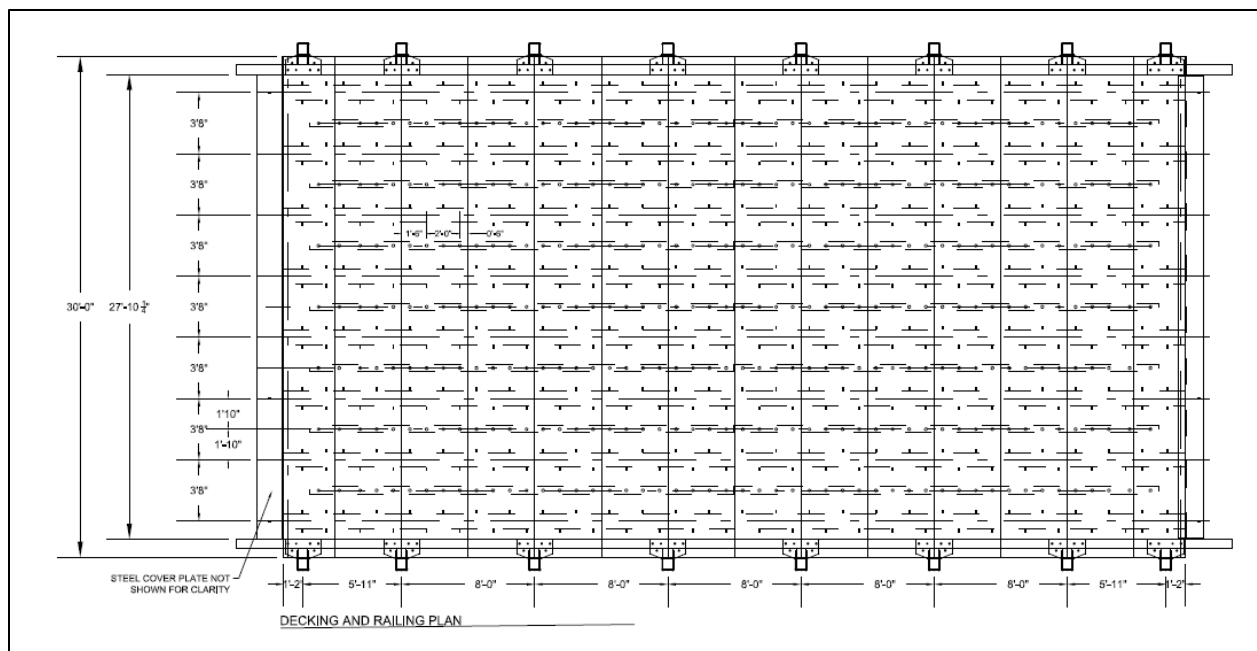


Figure 4.6 Plan view showing glulam deck, stiffeners, and railing.

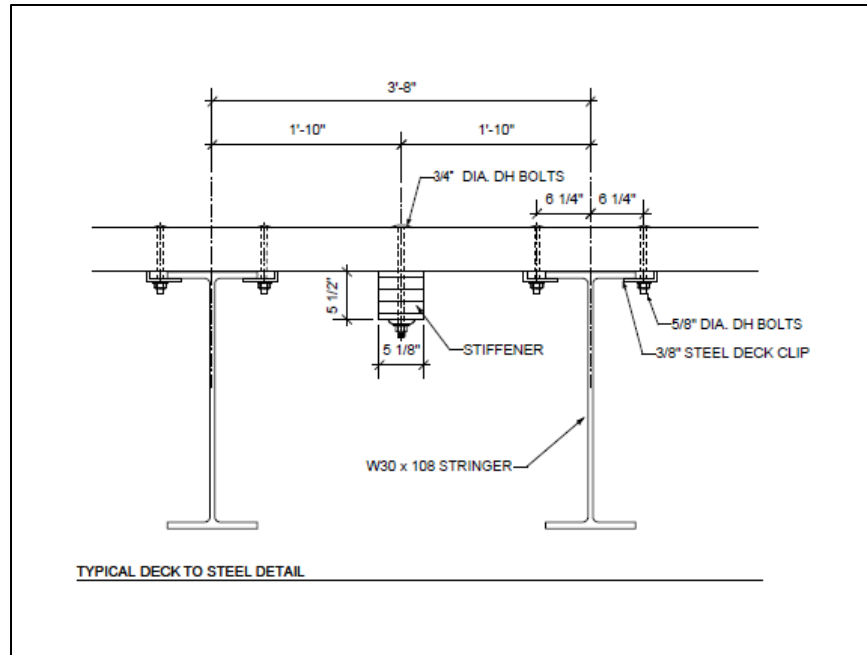


Figure 4.7 Deck and stiffener connections to steel girders detail.

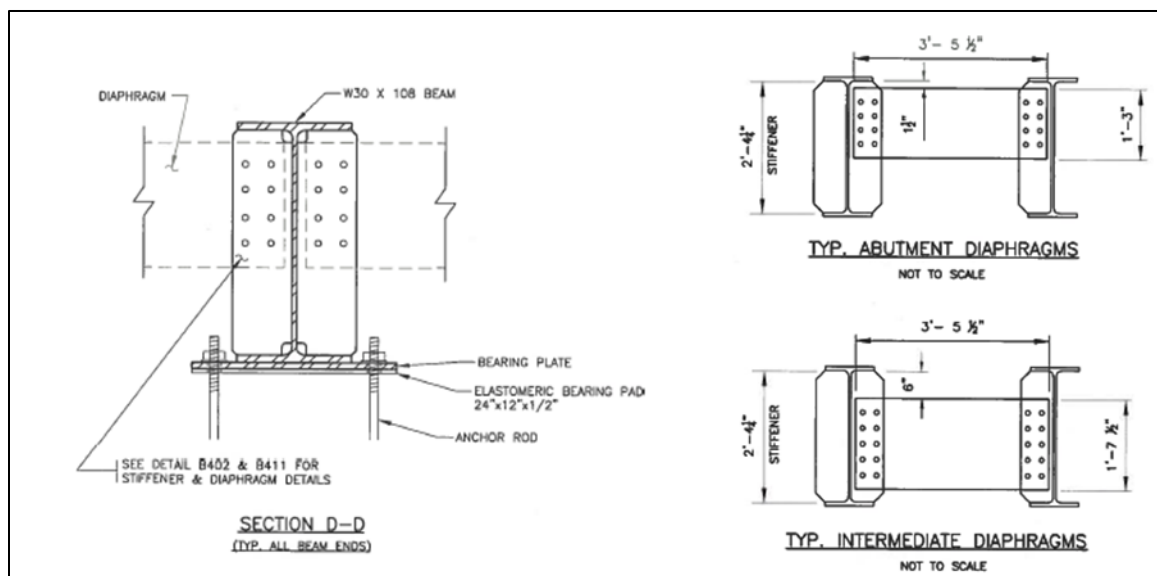


Figure 4.8 Diaphragm detail for steel girders.

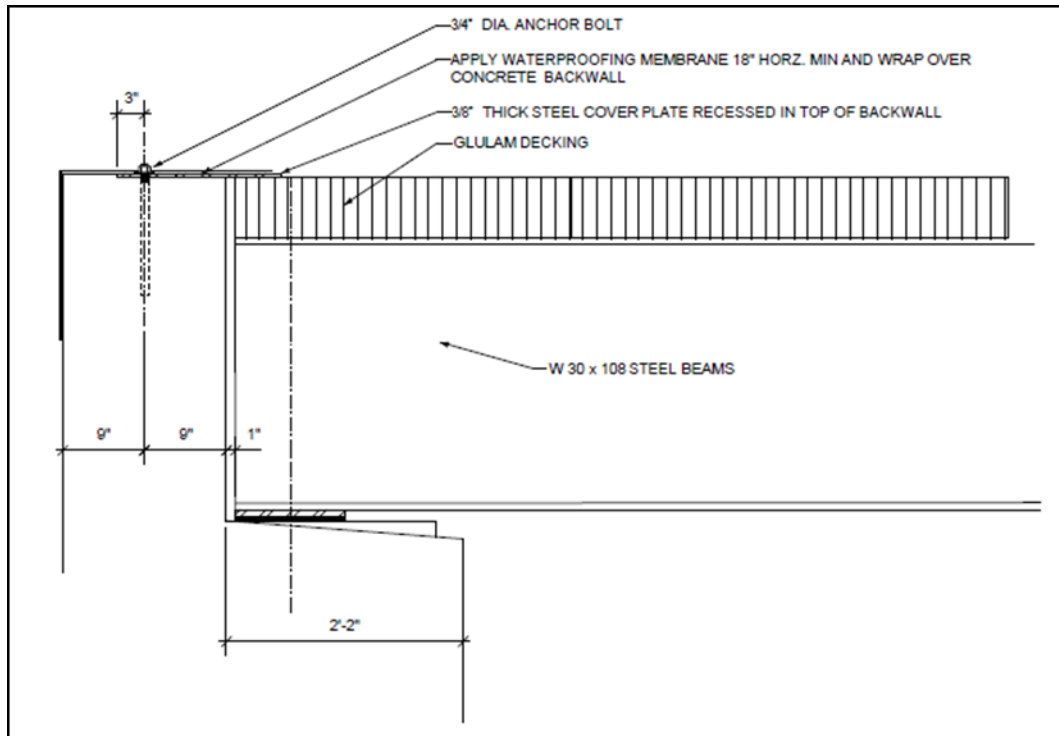


Figure 4.9 Profile view of bearing detail for SLC 516.

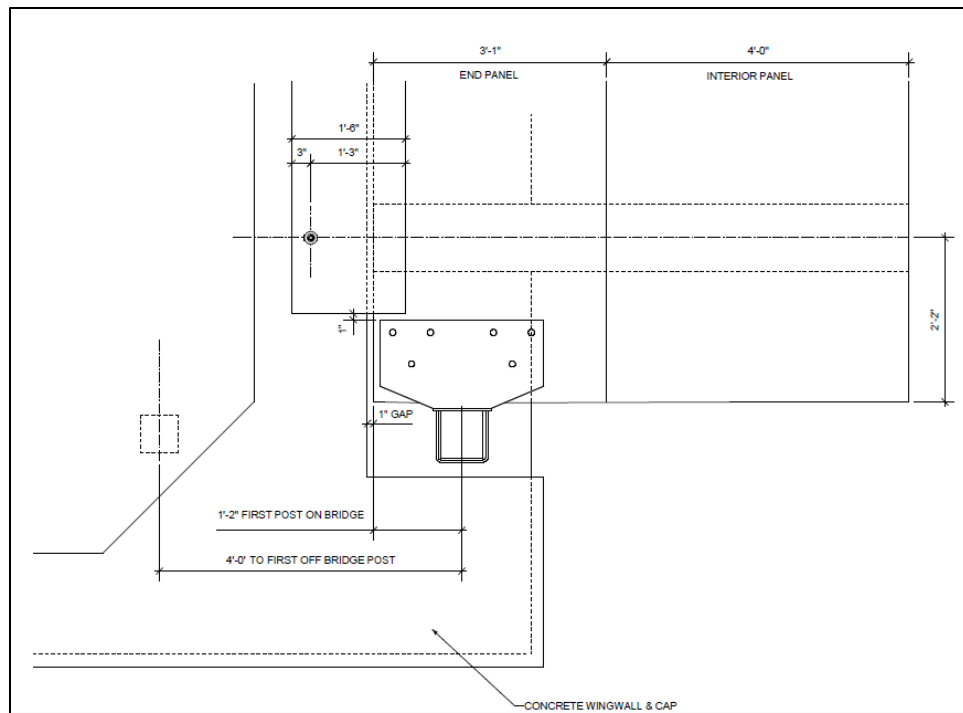


Figure 4.10 Top view of abutment, deck, and railing placement.

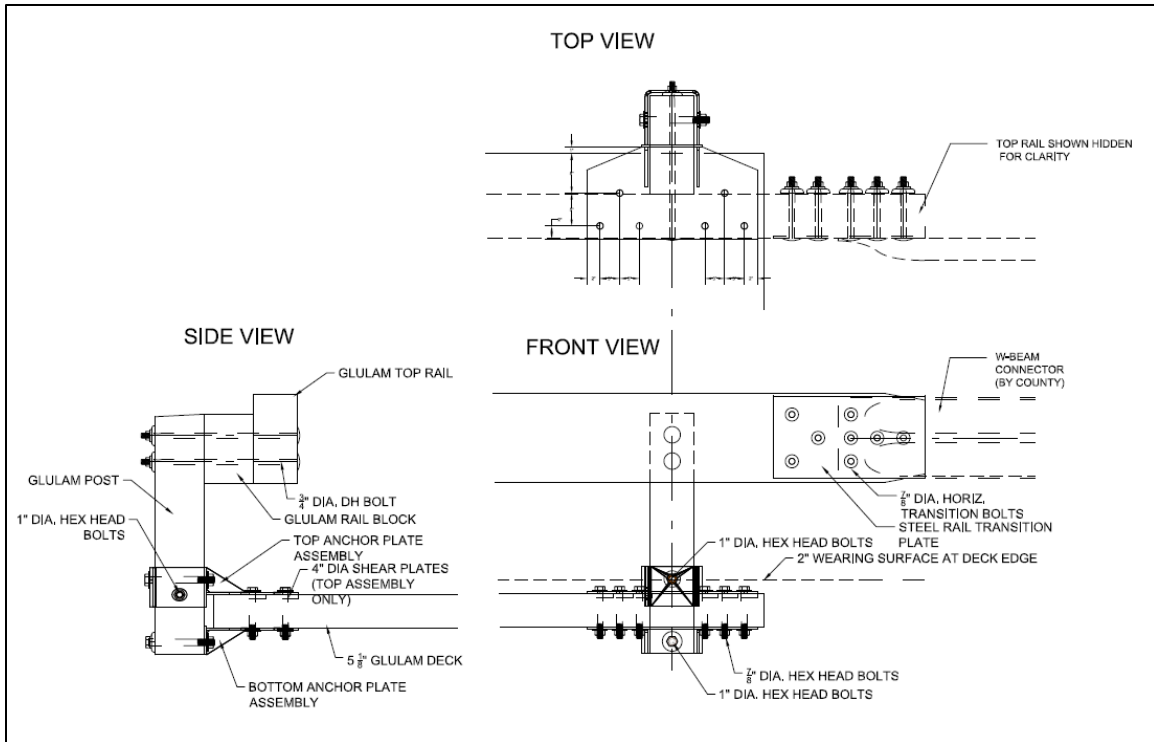


Figure 4.11 Guide rail detail.

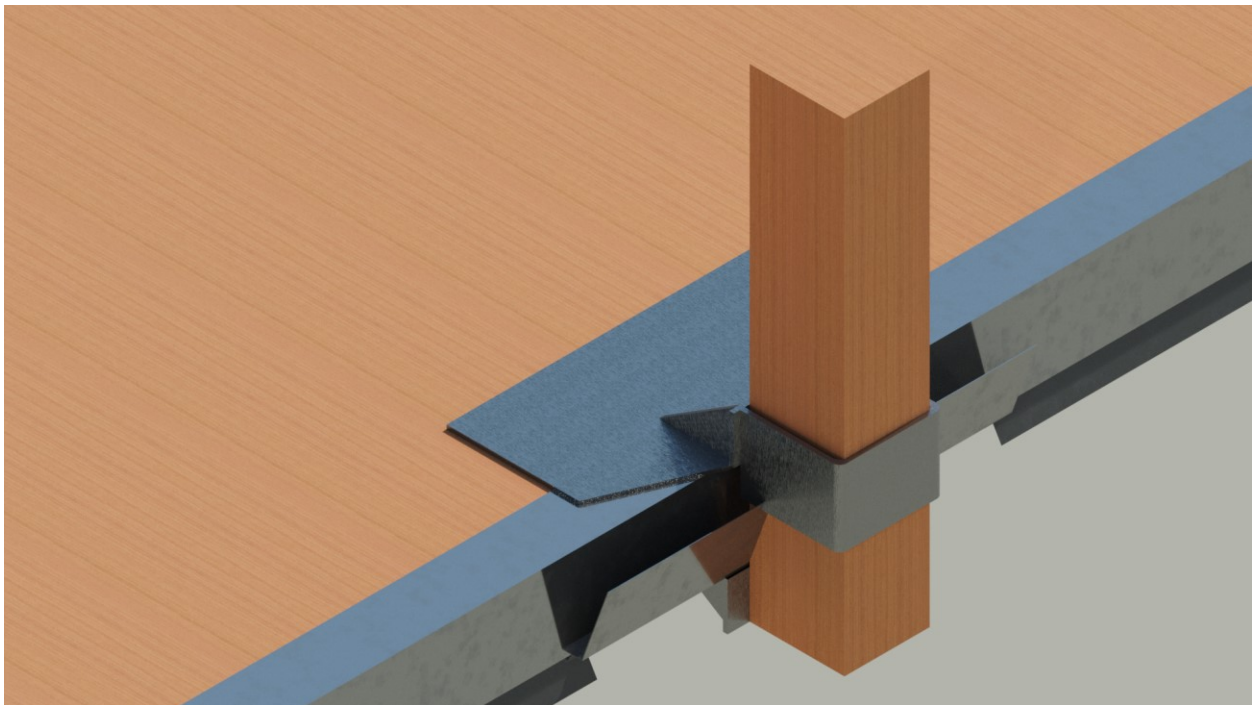


Figure 4.12 Three-dimensional rendering of proposed flashing detail between and at posts.

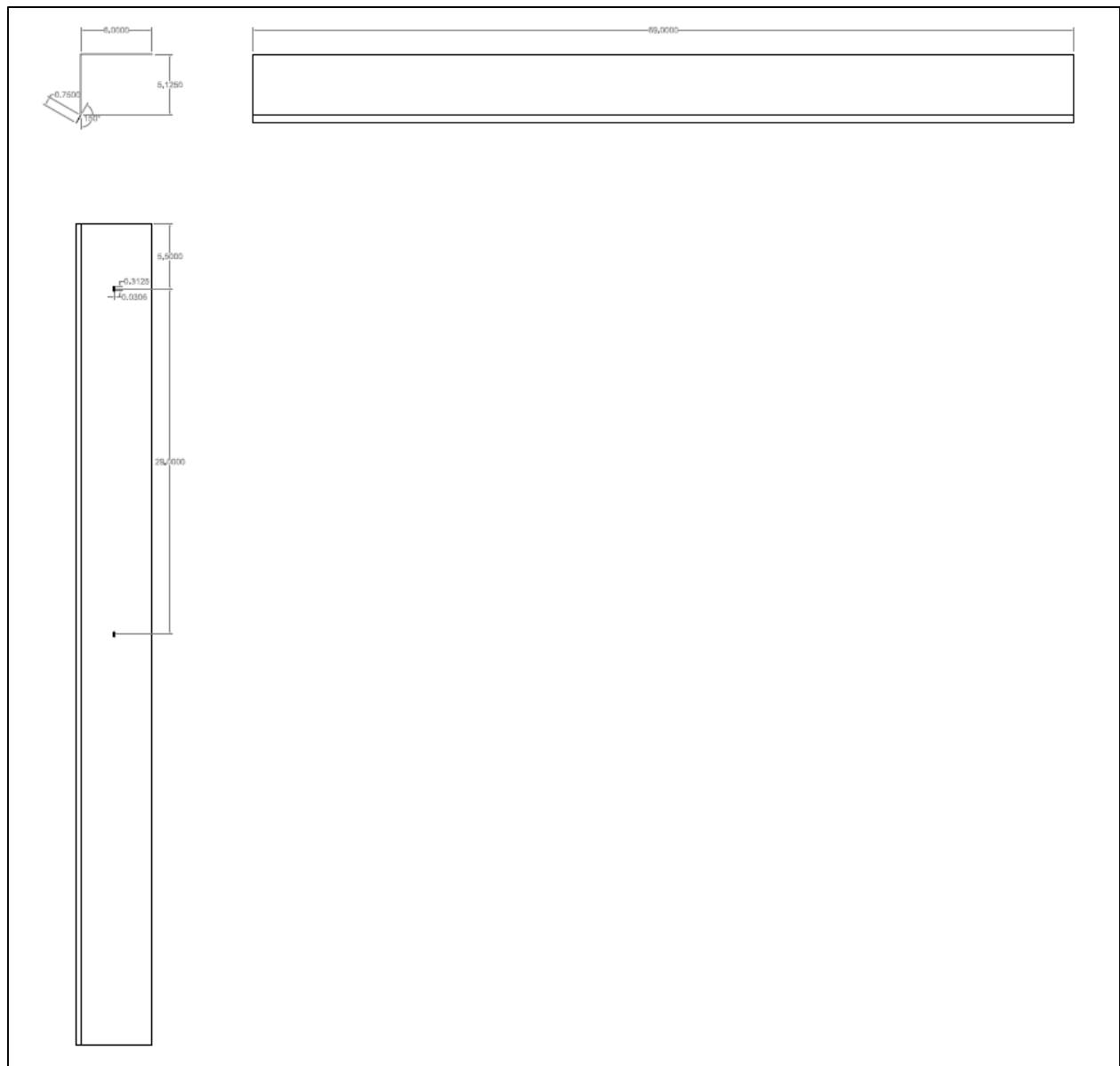


Figure 4.13 Shop drawings (3 orthogonal views) for the deck-edge flashing sections located between guardrail posts.

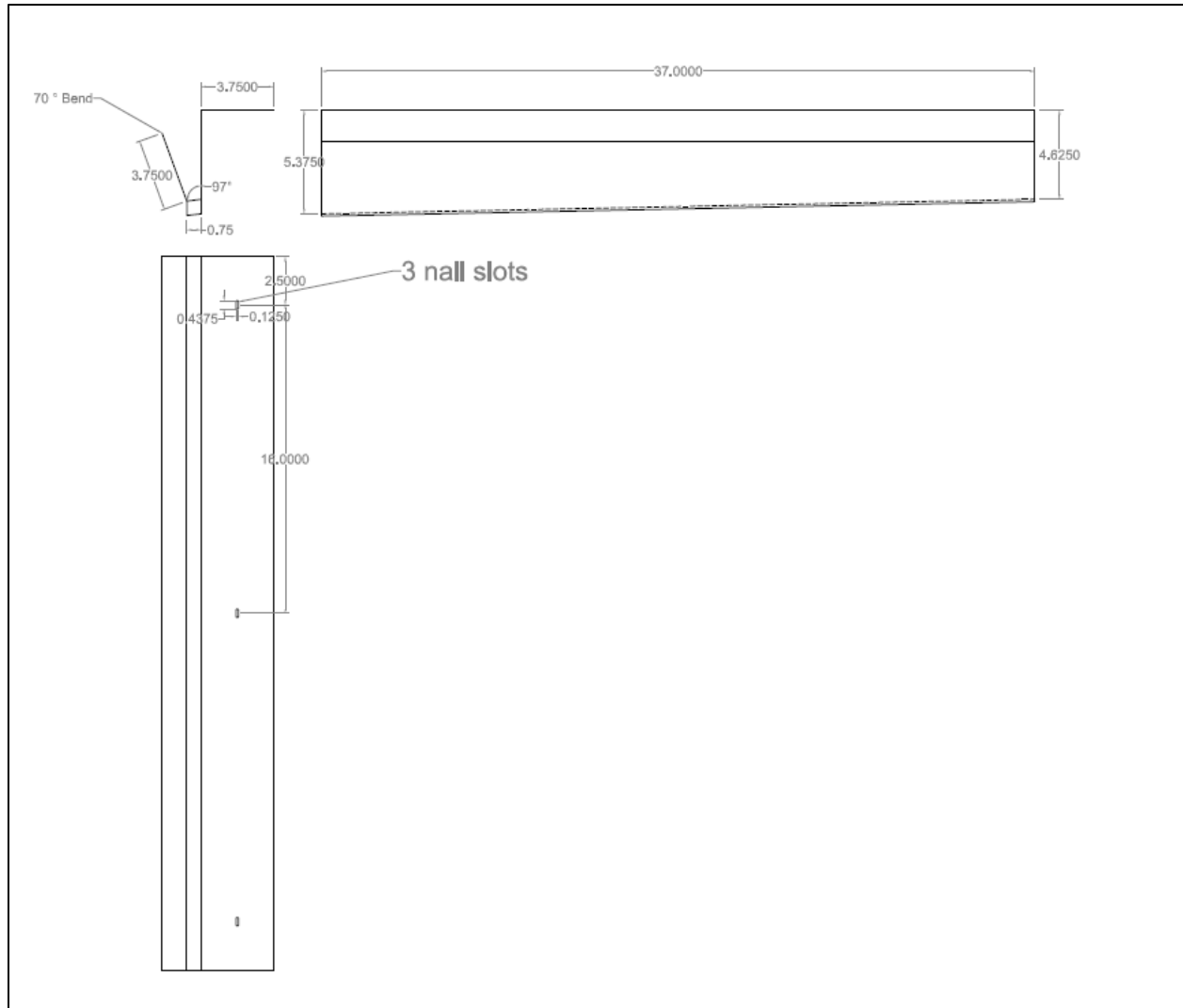


Figure 4.14 Shop drawings (3 orthogonal views) for the deck-edge flashing sections located at the guardrail posts.

4.2.1.2 Bid Process and Materials

STEEL BEAMS:

Based on the design specifications, St. Louis County solicited bids from outside vendors for the supply of the steel beams for use in this project. The steel beams were designated as W30 by 108 and including galvanizing. Two bids were received and the low bid was selected (Lejeune Steel Company). The materials were delivered to the bridge location and off-loaded by County personnel, and stored on site prior to installation.

TIMBER MATERIALS AND HARDWARE:

Based on the site parameters and design, St. Louis County distributed a bid package to three vendors in the Midwest. The bid information provided to the vendors is located in Appendix D. A formal bid application package was not prepared by the County, but instead relied on the design work completed by Laminated Concepts, Inc and approved by the County Engineer. Two bids were received for this project. The low bid was submitted was selected by St. Louis County (Bell Structural Solutions).

Based on the bid selection, shop drawings were submitted by the fabricator. However, based on the review of the drawings by the project team, the submitted shop drawings were rejected and resubmission requested. The following notes were provided to the fabricator at the time of rejection:

- Eliminate all references to field drilling.
- Provide full detailing of the deck clip for approval.
- Provide full detailing of the longitudinal stiffeners, include splice recommendations if any.
- Supplier should provide calculations to substantiate glulam grade proposed for decking.

The glulam supplier modified the shop drawings as requested and resubmitted them to St. Louis County for review. Based on the review, the comments had been addressed and corrected. The references to field drilling had been removed, full detailing of the deck clip was provided, thru-bolting slots measuring (2 in by 13/16 in) were included in the stiffeners, and a more appropriate glulam layup grade was proposed. The final shop drawings are included in Appendix D. They include a comprehensive part and material list and notes; plan and section views; and details for the glulam-to-steel beam connection, the glulam stiffener-to-glulam deck connection, and the guardrail system. Table 4.1 shows the wood material list and Table 4.2 shows the hardware material list for the bridge project.

Table 4.1 Wood material list for the project.

Number Required	Description	Size (in by in)	Length	Lamination Thickness Nominal (in)	Glulam Layup Combination
2	Deck Panel	5.125 by 37	30 ft 0 in	2	50
12	Deck Panel	5.125 by 48	30 ft 0 in	2	50
7	Stiffener	5.125 by 5.5	50 ft 0 in	2	48
16	Post	6.75 by 7.5	3 ft 13/16 in	2	48
16	Blocking	6.75 by 7.5	10 ½ in	2	47
2	Rail	6.75 by 13.5	58 ft 3 in	2	48

Table 4.2 Hardware material list for the project.

Quantity	Galvanized Description
16	Topside welded-plate assembly
16	Bottom side welded-plate assembly
4	3/16" X 12.25 x 23 plate
448	5/8" Ø X 7 1/2" DH grade bolt
350	3/4" Ø X 12" DH grade bolt
32	3/4" Ø X 24" DH grade bolt
32	7/8" Ø X 9" DH grade bolt
96	7/8" Ø X 7" machine bolt
48	1" Ø X 10" machine bolt
448	5/8" Ø nuts
382	3/4" Ø nuts
128	7/8" Ø nuts
48	1" Ø Nuts
382	3/4" Ø malleable washer
32	7/8" Ø malleable washer
16	1" Ø malleable washer
96	4" Ø (7/8" bolt) shear plate
448	3/8" deck clip

Note: Ø is the accepted symbol for diameter

Additional materials were ordered and are shown in Table 4.3. This included a steel plate for covering the gap between the abutment and the glulam deck and a waterproof membrane to cover the steel plate. This also includes bituminous overlay (SP Type 12.5 Wearing Course Mix) and a bituminous membrane that would serve as a reinforcing and waterproof layer between the two layers of bituminous. Bids were obtained for the bituminous material and paving services and the low bid was selected. A galvanized flashing was applied to the exterior edges of the glulam deck. It consists of an “at railing” post piece and a “between railing” post piece. In addition, four specific pieces were specified for the bridge ends over abutments.

Table 4.3 Materials for timber bridge superstructure.

Material	Supplier	Detail
Steel cover plate	Kraemer Construction, Inc. (Duluth, MN)	3 - 3/8" by 12 in by 10 ft, galvanized
Waterproof membrane for steel cover plate	Lowe's Home Improvement (Hibbing, MN)	Ice and water shield, 48 inch width
Bridge and deck waterproofing membrane	Manufacturer: Protecto Wrap Company (Denver, CO) Distributor: Wausau Supply Company (Schofield, WI)	M 400 A; 60 in by 50 ft by 70 mil thickness
Railing post cap	Laminated Concepts, Inc. (Big Flats, NY)	Plastic caps for rail posts to deflect water with screws
Rubber spacers and nails	Northern State Supply (Duluth, MN)	Galvanized screws and spacers for flashing
Galvanized deck flashings	Jamar Company (Duluth, MN)	Between post: galvanized 22 gauge – 10 pieces, 69 in long At post: galvanized 22 gauge – 12 pieces, 37 in long Bridge corner at post: galvanized 22 gauge – 14 pieces, 32 in long Bridge corner between post: galvanized 22 gauge – 14 pieces, 57 in long
Copper naphthenate	Copper Care Wood Preservatives, Inc. (Columbus, NE)	Preservative treatment for any on-site holes and cuts
Cold galvanizing compound	Manufacturer: Rust-Oleum Distributor: Lowes Home improvement (Hibbing, MN)	Repair of galvanized plates or other components

4.2.1.3 Construction

REMOVAL

The previous bridge was deconstructed and removed by St. Louis County personnel during the winter of 2017-2018.

CONCRETE ABUTMENT, WING WALL AND STEEL SHEET PILING WALL

Starting in March 2018, St. Louis County's northern bridge crew began constructing the new bridge. This included construction of a reinforced concrete abutment and sheet pile wing wall according to the plans in Appendix A. The site conditions were very difficult as the crew had to contend with very high water levels due to downstream beaver dams and high amounts of spring rainfall. To address the water, beaver dams were removed, and pumping was required during abutment construction. Figure 4.15

shows the upstream layout of the river. Figures 4.16, 4.17, 4.18, and 4.19 show the concrete abutments on the north end of the bridge and the concrete wing wall and the steel pile retaining wall.



Figure 4.15 Upstream view of the Embarrass River.



Figure 4.16 Concrete abutment, sheet pile wing wall and riprap to protect the roadway and bridge.



Figure 4.17 Upstream wing wall (driven sheet pile) with riprap to protect the roadway and bridge from scour erosion damages.



Figure 4.18 Downstream concrete abutment with riprap.

STEEL BEAMS

Eight steel beams (W30 by 108) were delivered and off-loaded at the jobsite. A crane was used to place each beam into location on steel bearing plates (0.75 in by 12in by 24 in) and neoprene pads that were attached to the abutment as shown in Figure 4.19. Steel diaphragms were attached to the beams as shown in Figures 4.20 and 4.21. The completed steel superstructure is shown in Figure 4.22. All the steel materials were galvanized.

The steel beams were installed using a crew of four individuals, which included one supervisor. The beams were installed over a three-day time period. Following installation of the beams, the bridge crew closed the construction site to await fabrication and delivery of the glulam materials.



Figure 4.19 Steel beams installed onto steel bearing plates with neoprene pads.



Figure 4.20 Steel diaphragm installation.



Figure 4.21 Steel diaphragm installation.



Figure 4.22 Installed steel beams and diaphragm stiffeners.

ENGINEERED GLULAM MATERIALS

Following acceptance of the bid, the fabricator, Bell Structural Solutions developed shop drawings for the project. Upon acceptance of the shop drawings by St. Louis County and the project team, glued-laminated deck, railings and posts were fabricated in Albert Lea, Minnesota. Following fabrication, holes and slots were predrilled into the materials based on the shop drawings. The wood materials were then transported to New Brighton, Minnesota and treated with pentachlorophenol wood preservative in a type A oil. Following treatment and certification, the glulam wood materials and hardware were transported to the bridge location and off-loaded. Care was used to ensure the materials were stored off the ground and a plastic tarp was used to cover the material prior to construction to minimize wetting from any rain events. Figures 4.23, 4.24, and 4.25 show the materials at the construction site prior to installation.



Figure 4.23 Glulam panels after delivery and unloading at the construction site.



Figure 4.24 Glulam stiffeners, railing, and panels after delivery.



Figure 4.25 Wood materials were covered with a plastic tarp to protect from rain.

A construction crane was used to move the wood materials into location. The glulam stiffeners were placed onto the bridge and then separated with one stiffener between each steel beam. The stiffeners were fabricated with a 13/16 in diameter slot that was 2 inches long to allow for easier insertion of the bolts through the glulam deck and the stiffener. It also allows for some dimensional movement of the wood materials due to changes in moisture content during its service life. One challenge noted was that approximately 20 thru-bolt locations, the insertion of the bolt conflicted with the steel diaphragms. Those bolts were field cut to a shorter length and installed, causing construction delays. The placement of the stiffener beams took approximately three man-hours. This included two installers and one crane operator. Figures 4.26, 4.27, 4.28, and 4.29 show the stiffeners being added to the superstructure.



Figure 4.26 Stiffeners were moved to the bridge deck using a crane.



Figure 4.27 Stiffeners were placed between each steel beam.



Figure 4.28 Stiffeners in place prior to deck installation.

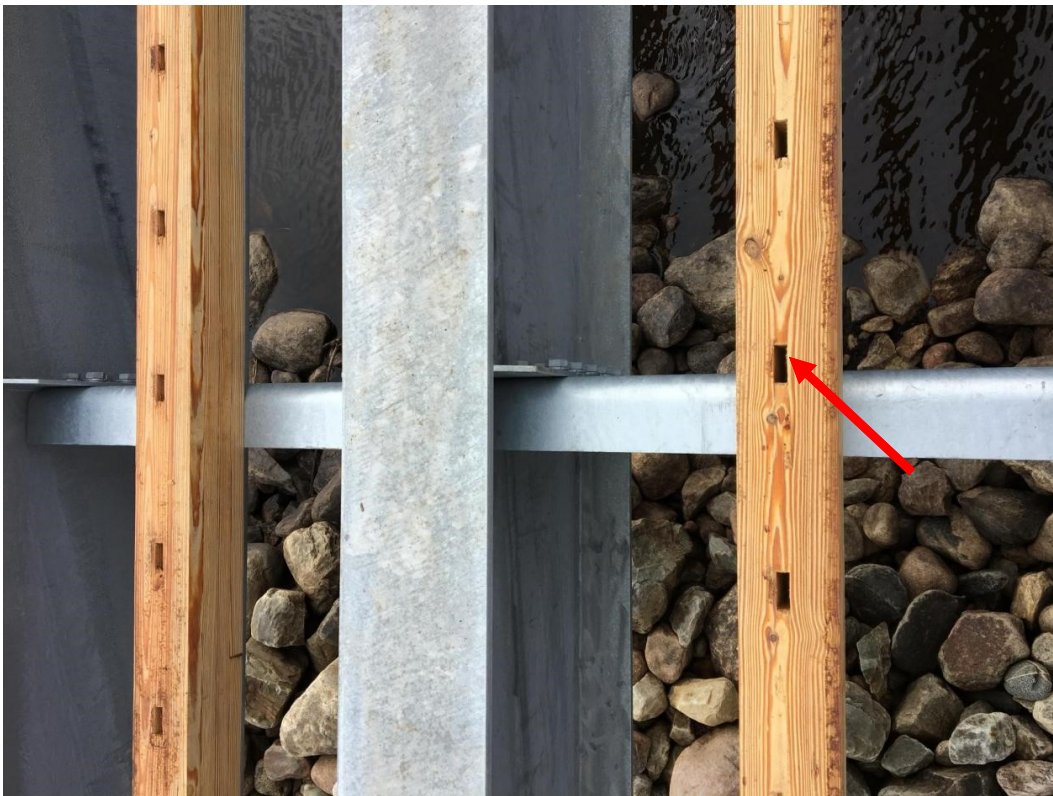


Figure 4.29 Machined slots for ease of bolt installation and dimensional movement.

Following placement of the stiffeners, the transverse glulam deck was installed onto the bridge, starting at the south end of the bridge and located on opposite end from the crane. Various techniques were used to align the panels into place and to ensure they were lined up end-to-end. This included the use of an excavator, sledge, and straps system using through bolts. The crew settled on the strap system where the crane lifted each panel into location and then pry bars were used to place the panels. A ratchet strap was also used to ensure the panels were tight edge-to-edge. The guard rail post hardware was also used to verify fit for the panels as they were installed. Deck clips were used to attach the glulam panels to the steel beams and bolts were used to connect the stiffeners to the glulam panels. Thirteen of fourteen panels were installed on day 1 and the remaining panel on day 2. The final panel had to be trimmed to width to account for as-built span dimensions between abutments. The panel cut edge was treated with several coats of copper naphthenate prior to installation. Fewer than five holes had to be drilled since they had not been drilled by the supplier. Each field drilled hole was treated with copper naphthenate preservative. Figures 4.30 to 4.42 show the deck during installation.



Figure 4.30 The first transverse panel was placed on the south side of the bridge.



Figure 4.31 A galvanized clip system was used to attach each panel to the steel beam.



Figure 4.32 Close-up of galvanized clip connection between panel and steel beam.



Figure 4.33 Additional panels were placed and connected to the steel beams.



Figure 4.34 Stiffener bolts were also installed during placement of the panels.



Figure 4.35 Panels were lifted using straps.



Figure 4.36 Close-up of glulam stiffener bolts, malleable washers and nuts.



Figure 4.37 Bottom side connections.



Figure 4.38 Ongoing installation of transverse deck panels



Figure 4.39 Post hardware was test fit to ensure proper panel placement.



Figure 4.40 A ratchet tightening system was used to ensure tight edge-to-edge.



Figure 4.41 Ongoing panel placement during day 1 of panel installation.



Figure 4.42 A tarp was placed onto the bridge deck to keep panels dry during construction.

CRASH-TESTED RAIL POST, FLASHING MATERIALS

To improve long-term durability of the timber materials, a flashing system was designed and fabricated. The system was designed to wrap over the exposed end grain of the wood panels, and to also drain water away from any post hardware locations. They were installed using galvanized decking screws, and a washer head to keep the end 1/16-1/8 in away from the end grain of the panels. Previously, Figures 4.12 to 4.14 show the CAD drawings of the drip edge flashing sections and Figures 4.43 to 4.47 show the installation of these pieces. The flashing materials were installed prior to installation of the post hardware, shown in Figures 4.48 to 4.50. The bridge material supplier made an error and sent two top plates, creating additional weight during installation. Due to a short construction window, a decision was made by the St. Louis County crew to use the materials as supplied and not wait for the correct bottom plate. The TL2 railing design drawings in the first section of this report show the proper hardware for future projects.

Grinding of the top surface of the north concrete abutment was necessary to ensure a flat surface between the timber deck and the abutment face. A steel plate was attached over the abutment and timber deck. This detail is intended to minimize any potential gravel or deterioration at the joint between the abutment and the timber deck. An ice and water barrier was specified to be installed over the plate but it was installed under the plate instead. Figure 4.51 shows the installed plate and water shield on the north abutment.



Figure 4.43 Washers attached to panel end-grain to create air space under the flashing.



Figure 4.44 Flashing between rail posts was installed first using galvanized roofing nails.



Figure 4.45 Flashing at posts was installed after the between post flashings.



Figure 4.46 Installed flashing to protect timber deck edge.



Figure 4.47 Short flashing sections were installed at the bridge corners.



Figure 4.48 Post hardware plates were installed prior to post installation.



Figure 4.49 Post hardware installed over the flashing.



Figure 4.50 Fully installed flashing and rail posts.



Figure 4.51 Waterproofing membrane and steel cover plate.

BITUMINOUS OVERLAY, WATERPROOF MEMBRANE

Following installation of the timber deck, flashing, rail posts and end plates, the roadway approaches were prepared for a bituminous overlay. Based on the bridge approach design in the St. Louis County construction plan (Appendix D), fill, grading, and compacting was completed as shown in Figures 4.52 to 4.56.

Following that process, bituminous overlay was installed by KTM Paving of Hermantown, MN. A tack coat applied to the timber bridge deck prior to paving. Bituminous SP Type 12.5 Wearing Course Mix was used for the project. A minimum of 10 ft of approach was paved with this mix. The bituminous was applied in two layers, for a final bridge edge thickness of 2 inches and a centerline thickness of 5.5 inches. A bituminous membrane overlay was applied to the bridge deck by St. Louis County crews between the layers. The membrane was provided by ProtectoWrap Company (Denver, CO), through their distributor, Wausau Supply Company (Schofield, WI). The product used was M 400 A. Each roll was 60 in by 50 ft by 70 mil thickness. The process steps for installation included:

Process steps:

- The bridge deck remained uncovered for 1-2 days prior to paving. If a major rain event is expected, it was covered during the rain event only.
- Wood paving edges were put in place prior to paving and removed after completion.
- A tack coat was applied to the timber deck.
- A base layer of bituminous (approximately one inch) was applied to the deck and compacted. It required hand rolling and tamping at the bituminous edge.
- The bituminous needed to cool to 175-200 °F prior to adding the ProtectoWrap membrane.
- The ProtectoWrap membrane was rolled out on the top of the base layer and went to within 1 inch of the bituminous edge. The rolls are 5 ft wide by 50 long. Overlap was two inches on the edges and 4 inches on the ends. The wrap extended 10 ft beyond the bridge deck onto the approach roadway. Pressure rolling was done to ensure adhesion, especially at overlapped seams.
- The wear course of bituminous was applied at between 275-300 °F.
- Final compaction and removal of wood paving edges was completed with tapered bituminous edges where the wood paving edges were located.

To ensure a paving edge on this curbless rail system, a temporary timber edge was installed prior to overlay. This is shown in Figures 4.57 to 4.59. It was then removed following the paving process. Figures 4.60 to 4.70 show the paving process and the installation of the waterproof reinforcing membrane.



Figure 4.52 Leveling the approach prior to bituminous installation.



Figure 4.53 Shaping and leveling the approach prior to bituminous installation.



Figure 4.54 Shaping in preparation of the bituminous wedge.



Figure 4.55 Vibratory compaction of the approach prior to bituminous installation.



Figure 4.56 Prepared approach prior to paving.



Figure 4.57 A temporary wood paving edge was developed and installed prior to overlay.



Figure 4.58 A wood paving edge close-up prior to overlay.



Figure 4.59 The bridge deck was swept clean, paving edge installed and ready for paving.



Figure 4.60 Multiple layers of bituminous were placed and compacted to create a wedge before the bridge.



Figure 4.61 Both approaches were prepared with a bituminous wedge.



Figure 4.62 A tack coat was applied to the timber deck surface and the bituminous wedge.



Figure 4.63 First layer of bituminous overlay being deposited onto timber deck.



Figure 4.64 Overlay work along paving edge.



Figure 4.65 Hand tamping of bituminous along paving edge.



Figure 4.66 Installation of waterproof membrane between layers of bituminous.



Figure 4.67 Each row of waterproof membrane was overlapped by 4 inches according to specifications.



Figure 4.68 Multiple rows of waterproof membrane installed on top of the bituminous layer.



Figure 4.69 A second layer of bituminous overlay was added on top of the membrane.



Figure 4.70 Second layer of bituminous added to the membrane.

GUARD RAIL, POST CAPS

Following paving, the temporary paving edges were removed from the bridge deck. The railing was installed according to the construction plan and design details. The guard rails were installed and attached to the bridge rails. Finally, a plastic cap was installed on top of each timber post to protect it from precipitation that can cause deterioration. Figures 4.71 to 4.75 show the bridge railing installation and connection to roadway guard rails.



Figure 4.71 Glulam railing installation.



Figure 4.72 Glulam rail installation.



Figure 4.73 Side view showing TL2 curbless rail system used on this bridge and the installed plastic cap for moisture protection.



Figure 4.74 Guard rail attached to the glulam rail system.



Figure 4.75 Guard rail on bridge approach.

Following completion of the bridge and approach guard rails, the road was opened for traffic. Figures 4.76 to 4.78 show the completed roadway and bridge.



Figure 4.76 Roadway open for traffic facing to the south.



Figure 4.77 Underside view of completed bridge.



Figure 4.78 Side view of completed superstructure.

4.2.1.4 Construction Time-Lapse Video

A Brinno Model TLC200 Pro camera was installed at the time work was initiated on the abutment. It was placed on a post in near proximity to the southeastern corner of the bridge project. Time-lapse photos were taken every five minutes during daylight hours during the construction project. A secure digital memory card was used to store the images. During construction, the card was replaced weekly. Unfortunately, a camera malfunction occurred during the installation of the glulam timber deck and railing posts. Following completion of construction, all images were then combined into a construction video that is available at: <https://www.cloudvault.usda.gov/index.php/s/2Y9QV4vAKHzUzXh>

4.2.1.5 Construction Lessons Learned

During the project design, bid, and construction process, significant lessons were learned that could support improvements in future timber bridge construction projects in Minnesota. These include:

1. This was a challenging site location due to the inherent river flow direction, water levels and weather. The river flow required significant site improvements, such as a sheet pile retaining wall and improved bank work. Further, culverts were installed under both road approaches to handle potential water flow and other drainage. The abutment work was done in late winter and spring of 2018 to ensure that the construction crew was out of the river by June 1. The high-water levels during the concrete work resulted in significant additional substructure costs, plus it resulted in modification to the abutment dimensions. For these reasons, the cost data and

estimates for alternate designs were limited to the superstructure of the bridge. This included the steel girders, transverse glulam deck, railings, and bituminous overlay. Labor and construction costs for deconstruction, site preparation, abutments, and other roadway work was not included in the data.

2. This project was done by St. Louis County bridge crews. At various times, both the north and south crews participated. Based on the bridge location, the travel time was approximately 60 minutes from Hibbing, Minnesota and 90 min from Pike Lake, Minnesota. These crews were responsible for all construction at the site, including deconstruction, site preparation, gravel delivery, abutment preparation, structural member installation, and final roadwork. The bituminous overlay and the approach guard rail installation was contracted and completed by an external vendor.
3. Improved bridge timber bid documents – It is suggested that a complete bid package be used and developed for purchase of the timber bridge materials. In this project, simple plans were (shown in Appendix B) were provided to potential timber materials suppliers. Additional specifications could include scope/description, qualification of bidder, design (calculations and load rating), shop drawings and bridge plans, material specifications, manufacturing specifications, measurement and payment.
4. The bids received allowed the construction team to select the lowest cost supplier for both the steel girders and the timber deck. For the steel girders, bids received showed that painted options of beams were \$2,250 – \$7,020 less than the hot dip galvanized system. The glulam timber deck with TL2 glulam railings was less cost than a dowel-laminated timber deck with a TL2 bridge rail by approximately \$2,500-4,000, depending on the glulam bid. Further, the dowel-laminated system does not have official crash-tested approval. The county selected southern yellow pine glulam for this project. The selection of Douglas fir glulam would have reduced the cost by approximately \$1,500.
5. Communication Meetings. While meetings were held with the project engineer and bridge supervisor in advance of the project, it is recommended that information be shared with the construction crew. This should include the bridge materials supplier, the county engineering staff, bridge superintendent and bridge foreman/crew. It would create additional awareness and familiarity with plan details, construction techniques, and a question/answer session.
6. In this project, slight changes were made to the bridge abutments during construction, resulting in a slightly decreased bridge span. However, this information was not communicated to the research team. Improved communication may have allowed the bridge designer and the timber fabricator to adjust the panel dimensions and eliminate the need to field cut the last timber panel. While the field cut was treated on the construction site with copper naphthenate preservative, it is not as effective as pressure treatment at the fabricator.
7. The timber material and hardware supplier made a mistake by sending two top anchor plates for the railings, instead of one top and one bottom anchor plate. By using top anchor plates for both the top and the bottom, it resulted in increased weight and more difficulty during installation.
8. Interviews with the county bridge superintendent, the bridge construction foreman, and the bridge construction crew resulted in good feedback for this project. Specifically, they identified the positive impact of having all holes pre-drilled, which significantly resulted in shorter installation times. This also affirmed the importance of having slots instead of holes pre-drilled into the stiffener beams, as it allowed for easy installation. Other benefits noted included rapid

overall construction, low odors on the job site, minimal on-site fabrication, and a quiet construction site. They noted the negative to cutting the panel to size on site, the increased weight in the guard rail anchor plates (resulting from using a top plate for the bottom plate based on supplier error). They reported that the membrane that was placed between layers was very simple and easier than expected. It took less than one-man hour to install.

9. Perhaps the most valuable aspect to the timber construction is a compressed construction cycle. For this project, steel beams were placed and installed in five workdays, the timber deck completed in four workdays, railing posts, hardware, and rails in three workdays. While this project was significantly delayed due to other aspects, the actual construction time was minimized.

4.3 COST SUMMARY AND COMPARISON

4.3.1 As-built Design: Steel Girders and Transverse Glulam Panels

One of the goals of this project was to track and compare costs for this bridge as compared to other options. Table 4.4 provides cost estimates for the superstructure of this bridge, to include the steel beams, glulam panels, railings, durability details, and bituminous overlay. The completion of the abutments was the zero cost point for this bridge. This simplifies the cost tracking and comparisons for the project, since there was substantial site work and other complications that were site and weather specific. The construction progress was documented and the duration for each installation was:

- Steel beam installation (5 workdays)
- Timber deck installation (4 workdays)
- Railing posts, hardware (3 workdays)
- Bituminous overlay (1 workday)

Table 4.4 Cost breakdown for St. Louis County Bridge 516.

Category	Materials	Labor	Total
Superstructure – Steel ¹	\$99,800	\$10,735	\$110,535
Superstructure – Glulam southern yellow pine, penta treatment ²	\$72,316	\$9361	\$81,677
Superstructure – Abutment steel plate	\$3,210	\$450	\$3,660
Superstructure – Wearing Surface	\$22,276 (installed)	\$1,350	\$23,626
Superstructure – Waterproof membrane	\$2,411	\$125	\$2,536
Superstructure – Deck flashing	\$856	\$500	\$1,356
Superstructure – Miscellaneous supplies	\$400		\$400
Superstructure Total	\$222,619	\$22,521	\$245,140
Guard Rails - Steel	\$21,350 (Installed)		\$21,350

Notes:

¹Paint Options: deduct \$2,250 for zinc primer with epoxy intermediate coat and urethane topcoat; deduct \$7,020 for epoxy primer and urethane topcoat

²Glulam Options: deduct \$1,417 for Douglas fir; add \$2,414 for dowel-laminated panels with glulam bridge rails

4.3.2 Alternative Design: Rolled Steel Beam with Concrete Deck

Additional cost comparisons/engineer's estimates were completed by LHB Engineering. This engineer's estimate was based on a 57.33-ft-long, 36-in steel wide flange beam span (55.17 ft bearing to bearing) with a 9-in concrete deck and a combination concrete and steel barrier. The general criteria used for determining estimate and unit process was:

- Estimate is built off as-designed abutments for SLC Bridge #516. The estimate accounts for new superstructure and theoretical alterations to the as-designed abutments to support the new superstructure.
- 28 ft – 0 in roadway and 31 ft – 4 in bridge deck out-to-out width
- 6 lines of W30X99 (galvanized) at 5 ft - 5 ½ in spacing between beams
- One-hundred (100) feet of 10 in steel pile added to account for additional superstructure dead load from concrete deck.
- Two additional cubic yards of structural concrete added to account for deeper superstructure

Figure 4.79 shows the design transverse section. Table 4.5 is an estimate of quantities and cost.

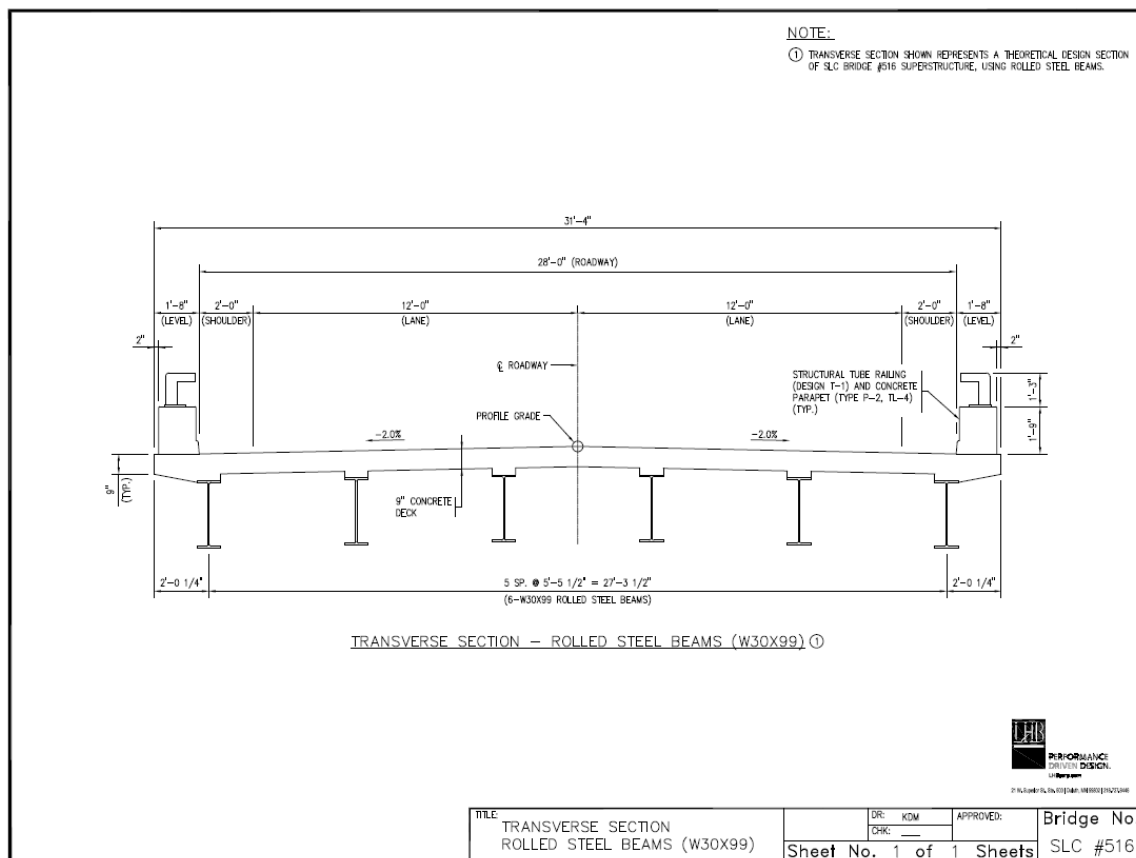


Figure 4.79 Transverse section of rolled steel beam with a concrete deck superstructure.

Table 4.5 Rolled steel beam with concrete deck bridge estimated quantities and costs

Item No.	Description	Units	Quantity	Unit Price	Total Price
2021.501	Mobilization	Lump Sum	1	\$17,000.00	\$17,000.00
2401.501	Structural Concrete (3b52) (P)	Cu Yd	2	\$1,000.00	\$2,000.00
2401.512	Bridge Slab Concrete (3y42-M) (P)	Sq. Ft	1796	\$31.00	\$55,676.00
2401.513	Type P-2 (TI-4) Barrier Concrete (3s52) (P)	Lin Ft	115	\$115.00	\$13,225.00
2401.541	Reinforcement Bars (Epoxy Coated) (P)	Pound	12000	\$1.75	\$21,000.00
2401.541	Reinforcement Bars (Stainless-60ksi) (P)	Pound	320	\$5.00	\$1,600.00
2402.508	Structural Steel (3309)	Pound	40000	\$3.25	\$130,000.00
2402.584	Structural Tube Railing Design T-1 (P)	Lin Ft	103	\$130.00	\$13,390.00
2402.590	Elastomeric Bearing Pad Type 1	Each	12	\$200.00	\$2,400.00
Total					\$260,491.00

Note:

- Items per the 2016 Edition of the Minnesota Department of Transportation Standard Specifications for Construction.
- It was estimated by LHB, Inc. that the superstructure construction duration would be 6-8 weeks minimum.

4.3.3 Alternative Design: Rectangular Prestressed Concrete Beam with Concrete Deck

Additional cost comparisons/engineer's estimates were completed by LHB Engineering. This engineer's estimate was based on a 57.33 ft prestressed concrete beam span (55.17 ft bearing to bearing) with 9 in concrete deck and a combination concrete and steel barrier. The general criteria used for determining estimate and unit process was:

- Estimate is built off as-designed abutments for SLC Bridge #516. The estimate accounts for new superstructure and theoretical alterations to the as-designed abutments to support the new superstructure.
- 28 ft – 0 in roadway and 31 ft – 4 in bridge deck out-to-out width
- 5 lines of 22 in rectangular prestressed concrete beams (22RB) at 6 ft – 8 in spacing between beams
- One-hundred (100) feet of 10 in steel pile added to account for additional superstructure dead load from concrete deck.

Figure 4.80 shows the transverse section of this design and Table 4.6 shows the statement of estimate quantities and cost.



Table 4.6 Rolled steel beam with concrete deck bridge estimated quantities and costs.

Item No.	Description	Units	Quantity	Unit Price	Total Price
2021.501	Mobilization	Lump Sum	1	\$13,000.00	\$13,000.00
2401.512	Bridge Slab Concrete (3y42-M) (P)	Sq. Ft	1796	\$31.00	\$55,676.00
2401.513	Type P-2 (TI-4) Barrier Concrete (3s52) (P)	Lin Ft	115	\$115.00	\$13,225.00
2401.541	Reinforcement Bars (Epoxy Coated) (P)	Pound	12000	\$1.75	\$21,000.00
2401.541	Reinforcement Bars (Stainless-60ksi) (P)	Pound	320	\$5.00	\$1,600.00
2402.584	Structural Tube Railing Design T-1 (P)	Lin Ft	103	\$130.00	\$13,390.00
2402.590	Elastomeric Bearing Pad Type 1	Each	10	\$200.00	\$2,000.00
2405.502	Prestressed Concrete Beams 22rb (P)	Lin Ft	282	\$290.00	\$81,780.00
2452.603	Steel H-Piling 10"	Lin Ft	100	\$42.00	\$4,200.00
Total					\$205,871.00

Note:

- Items per the 2016 Edition of the Minnesota Department of Transportation Standard Specifications for Construction.
- It was estimated by LHB that the superstructure construction duration would be 6-8 weeks minimum.

Life-cycle cost assessments (LCCA) are often completed for transportation construction projects to assess the full service life costs for these projects. For this project, the comparisons for LCCA were limited to the superstructure construction and maintenance costs. Other LCCA estimates may include the cost of inspection and user costs.

For the as-built timber design and the two concrete alternatives, the following information was projected. This includes the initial construction costs, and rehabilitation costs for both the first and second rehabilitation. For this project, an estimated life of the bridge was estimated at 75 years. For this case, deck rehabilitation was estimated at 25 and 50 years for the timber project and 25 and 50 years for the concrete deck project. Estimates of deck repairs was estimated at \$30,000 (2018 dollars) was estimated at 25 years and 50 years for the timber deck and at 50 years for the concrete deck options. Repair and rehabilitation options for the concrete deck could include repair of potholes, shallow overlay, and bridge deck replacement. Further maintenance could include pothole repairs at 10-year time intervals.

4.4 LIFE-CYCLE ANALYSIS

A preliminary, screening cradle-to-gate life-cycle assessment (LCA) was completed for St. Louis County, Minnesota bridge 516, which was constructed approximately 7.4 miles W/SW of Babbitt, Minnesota over the Embarrass River. The LCA utilized data from the bill of materials (BOM) and construction drawings, which were provided by the project team.

The system boundary included material and fuel consumption for timber and steel structural materials fabrication; material and fuel consumption for fabrication of steel hardware, bituminous overlay, and related components; and transport of materials to the construction site. Because this preliminary screening LCA study was cradle-to-gate, use phase activities and disposal/recycling of the timber bridge were excluded. Most of the life-cycle inventory (LCI) data was secondary data from the DATASmart LCI database (LTS, 2019a). This study also used the cut-off approach method for recycling and utilized the LTS 2019 method (LTS, 2019b) to translate the LCI data into environmental impacts, which combines the ReCiPe Endpoint (H) v1.03 method's (Huijbregts et al., 2017) three endpoint categories (Human Health, Ecosystems, Resources) with the Cumulative Energy Demand, Climate Change, and Water Use impact categories.

A screening LCA is helpful to identify where in the product life cycle most environmental impacts occur, as well as which environmental areas are most impacted. This helps in the definition of the goal and scope of future work, if desirable. The screening LCA may also serve as a guide for a full LCA and allow for the refinement of the goal and scope moving forward, while forming the basis of the model for the full LCA. Since a screening-level LCA may use simplified assumptions, the results are only as accurate as those assumptions.

This study was modeled using *SimaPro v9.0* LCA software (Pré, 2016) and follows International Organization for Standardization (ISO) 14044 guidelines (ISO, 2006a) for internal screening LCAs; however, this LCA is not ISO-approved and is not suitable for external statements or documentation. Screening-level LCAs are used for gathering and analyzing internal information and allow for assumptions and the use of proxy data and do not usually include the exhaustive sensitivity, consistency, or uncertainty analyses required to comply with ISO 14044 guidelines for public disclosure.

4.4.1 GOAL AND SCOPE DEFINITION

The first phase of an LCA defines the goal and scope of the study. According to ISO 14044, the goal of the study should clearly specify the intended application, reasons for carrying out the study, the intended audience, and whether the results are intended to be disclosed to the public. The scope of the study describes the most important aspects of the study, including the functional unit, system boundaries, cut-off criterion, allocation, impact assessment method assumptions, and limitations. The objective of this study was to determine the potential environmental impacts of St. Louis County, Minnesota bridge 516. The results could be used to inform the Minnesota Department of Transportation (MnDOT) and their stakeholders of the environmental profile of the bridge.

4.4.1.1 Function

The function of the bridge is to support automobile, pedestrian, and bicycle traffic over the Embarrass River.

4.4.1.2 Functional Unit

A functional unit identifies the primary function(s) of a system based on which alternative systems are considered functionally equivalent (ISO, 2006b). This facilitates the determination of reference flows for each system, which in turn facilitates the comparison of two or more systems. Based on the identified function, the following functional unit was used to determine the reference flows: one steel girder and glulam bridge with a width of 30 ft and a length of 54 ft.

4.4.1.3 System Boundaries

System boundaries are established in LCA in order to include the significant life-cycle stages and unit processes, as well as the associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life-cycle stages, and the flows associated with each alternative, are considered. Included in the system boundary of this study are:

- Material and fuel consumption for timber and structural steel materials fabrication;
- Material and fuel consumption for fabrication of steel hardware and related components;
- Material and fuel consumption for bituminous overlay; and
- Transport of materials to the construction site.

4.4.2 Excluded Processes

Because this preliminary screening LCA study is cradle-to-gate, use-phase activities and disposal/recycling of the bridge components are excluded. Also, the use of cold galvanizing compound was excluded because no LCI data exists; materials packaging is also excluded from the study. Typically, in an LCA, some aspects within the set boundaries are excluded due to statistical insignificance or irrelevancy to the goal and scope. Thus, the following impacts were also excluded from the scope and boundaries for this study:

- Human activities (e.g., employee travel to and from work); and
- Services (e.g., the use of purchased marketing, consultancy services and business travel).

4.4.3 Cut-off Criteria

Cut-off criteria are often used in LCA practice for the selection of processes or flows to be included in the system boundary. The processes or flows below these cut-offs or thresholds are excluded from the study. Several criteria are used in LCA practice to decide which inputs are to be considered, including mass, energy and environmental relevance. In the current study, every effort was made to include all the flows associated with the processes studied. During the interpretation phase, we used 1% of environmental load as a cut-off.

4.4.4 Allocation and Recycling

While conducting an LCA, if the life cycles of more than one product are connected, allocation of the process inputs should be avoided by using the system boundary expansion approach. If allocation cannot be avoided, an allocation method – based on physical causality (mass or energy content, for example) or any other relationship, such as economic value – should be used (ISO, 2006a). All allocations were completed based on mass.

This study used the cut-off approach method for recycling. According to this approach, the first life of a material bears the environmental burdens of its production (e.g., raw material extraction and processing) and the second life bears the burdens of refurbishment (e.g., collection and refining of scrap). The burdens from waste treatment are taken by the life after which they occur (Frischknecht, 2010). Given that DATASMART LCI data (LTS, 2019a) uses the cut-off approach for recycling, it is considered a reasonable default.

4.4.5 Impact Assessment Method

Impact assessment methods are used to convert LCI data (environmental emissions and raw material extractions) into a set of environmental impacts. ISO 14044 (ISO, 2006a) does not dictate which impact assessment method to use for a comparative assertion; however, the chosen method needs to be an internationally-accepted method if the results are intended to be used to support a comparative assertion disclosed to the public.

The impact assessment method used for this study was the LTS 2019 method (LTS, 2019b), which combines the ReCiPe Endpoint (H) v1.03 method's (Huijbregts et al., 2017) three endpoint categories (Human Health, Ecosystems, Resources) with the Cumulative Energy Demand (CED) v1.11 (Frischknecht, et al. 2007), Climate Change IPCC 2013 GWP 100a v1.03 (IPCC, 2013), and Water Use (Huijbregts et al., 2017) impact categories. These six categories have been found to be of interest and readily understandable to readers of LCA reports. The LTS 2019 method (LTS, 2019b) is summarized in Table 4.7.

Table 4.7 LTS 2019 method (LTS, 2019b).

Impact Category	Method	Unit
Human Health	ReCiPe 2016 Endpoint (H) v1.03	DALY
Ecosystems	ReCiPe 2016 Endpoint (H) v1.03	species*yr
Resources	ReCiPe 2016 Endpoint (H) v1.03	\$
Cumulative Energy Demand	CED v1.11	MJ
Climate Change	IPCC 2013 GWP 100a v1.03	kg CO ₂ eq.
Water Use	ReCiPe 2016 Endpoint (H) v1.03	m ³

ReCiPe is one of the most recent and updated impact assessment methods available to LCA practitioners. The method addresses several environmental concerns at the midpoint level and then aggregates the midpoints into a set of three endpoint categories. Endpoint characterization models the impact on Areas of Protection (i.e., on human health, ecosystems, and resources). In other words, endpoint is a measure of the damage – at the end of the cause-effect chain – caused by a stressor in terms of human life-years lost and the years lived disabled, species disappeared, and resources lost.

The Cumulative Energy Demand (CED) of a product is the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal. The CED method considers both renewable and non-renewable energy and the direct and indirect energy consumption.

The IPCC 2013 method for assessing the Global Warming Potential (i.e., Climate Change) was developed by International Panel on Climate Change (IPCC). It is one of the most widely used methods to estimate climate change potential of global warming gases in LCA studies. The global warming factors have been developed for 20-, 100-, and 500-year time horizons to address the global warming potential of emissions in the short as well as long term. This study uses the climate change factors for the 100-year time horizon.

4.4.5.1 Endpoint Categories

- **Human Health.** In this category, the damage analysis links the six midpoint categories (Climate Change, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter Formation, Ionizing Radiation, and Ozone Depletion) to the Disability Adjusted Life Years (DALYs). The DALY tool is primarily a disability weighting scale of 0 – 1, where 0 represents perfect health and 1 represents death.
- **Ecosystems.** The damage to ecosystems is measured by calculating the species that disappear in each time period and area. The unit of damage assessment is species lost in one year (species*yr). The midpoint impact potentials that apply to ecosystem quality are: Climate Change, Terrestrial Acidification, Freshwater Eutrophication, Ecotoxicity, Agricultural Land Occupation, Urban Land Occupation, and Natural Land Transformation.
- **Resources.** The two midpoint categories contributing to the resources category are Fossil Depletion and Metal Depletion. The quantification of the damage is based on the marginal increase of cost due to the extraction of resources, measured as dollars per kilogram (\$/kg).

4.4.5.2 Midpoint Categories

- **Cumulative Energy Demand.** This category includes non-renewable (fossil and nuclear) and renewable (biomass, water, solar, wind, and geothermal) energy sources. Characterization factors are based on the upper (or higher) heating value. Characterization factors are expressed as equivalent megajoules (MJ).
- **Climate Change.** There are several gaseous emissions that cause global warming, including carbon dioxide, methane, nitrous oxides, and fluorinated gases. This category combines the effect of the periods of time that the various greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared. The global warming potential is measured as kg

equivalents of radiation CO₂ (i.e., the relative global warming potential of a gas as compared to CO₂). The IPCC model with a 100-year time horizon is used for characterization. The uptake of CO₂ from the air (i.e., sequestration of CO₂ by plants) and the subsequent emission of biogenic CO₂ (from the burning of biomass) is not included.

- **Water Use.** Water use is based on water consumption, which is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea (Falkenmark et al. 2004). Water that has been consumed, therefore, is no longer available in the watershed of origin for humans nor for ecosystems.

4.4.6 Limitations of the Study

This is a cradle-to-gate screening LCA using primary and secondary data. To make external claims per ISO 14044 (ISO, 2006a), this study would need to be expanded to include:

- Cradle-to-grave system boundary (to include distribution transport, use, and end-of-life phases);
- Primary data for key processes;
- Additional sensitivity analyses;
- Data quality requirements and indicators; and
- Critical review.

4.4.7 Limitations of LCA Methodology

LCA's ability to consider the entire life cycle of a product makes it an attractive tool for the assessment of potential environmental impacts. Nevertheless, like other environmental management analysis tools, LCA has several limitations.

With current availability of data, it is nearly impossible to follow the entire supply chain associated with the product life in a company- or manufacturer-specific way. Instead, almost all processes within the supply chains are modeled using average industry data with varying amounts of specificity (e.g., data on a more-or-less specific technology or region). This makes it difficult to accurately determine how well the unit process data represents the actual factors in the products' life cycle. It also makes it difficult to know in which region the processes are found.

Furthermore, LCA is based on a linear extrapolation of emissions with the assumption that all the emissions contribute to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while the linear extrapolation is a reasonable approach for more global and regional impact categories such as Global Warming Potential (GWP) and Acidification, it may not accurately represent the actual on-the-ground human- and ecotoxicity-related impacts.

Additionally, even if the study has been critically reviewed, it should be noted that, as for any LCA, the impact assessment results generated for this study are relative expressions and do not predict impacts on category midpoints, exceeding thresholds, or risks. It should also be noted that, even though LCA covers a wide range of environmental impact categories, some types of environmental impacts (e.g., noise, social, and economic impacts) are typically not included in LCA.

4.4.8 Life-Cycle Inventory

The second phase of an LCA is to collect life-cycle inventory (LCI) data. LCI data contains the details of the resources flowing into a process and the emissions flowing from a process to air, soil, and water.

4.4.8.1 LCI Data Collection

As previously noted, only some primary inventory data was used in this study. The primary data was mainly for transportation inputs from the glulam manufacturing and asphalt plants to the bridge construction site. Secondary/background data was used for the remaining processes, with most it readily available in the DATASmart LCI database (LTS, 2019a).

TIMBER MATERIALS PRODUCTION

The deck panels (5.125-in x 37-in x 30-ft and 5.125-in x 48-in x 30-ft), stiffeners, posts, blocking, and rails were all manufactured from pentachlorophenol-treated glued timber (glulam) designed for outdoor use. The glulam was assumed to be manufactured from softwood at 20% moisture content and bonded with a melamine formaldehyde resin. It was assumed that the yield loss in manufacturing the glulam products was 10% by weight. Selected life-cycle inventory data for the pentachlorophenol-treated glulam are listed in Table 4.8.

Table 4.8 Selected life-cycle inventory data for 1,000 ft³ of pentachlorophenol-treated glulam.

Description	LCI Data Source	Quantity	Unit
Water	Water, unspecified natural origin, US	1.3×10^0	gal
LPG	Liquefied petroleum gas, combusted in industrial boiler NREL/US U	7.9×10^{-1}	gal
Diesel	Diesel, combusted in industrial equipment NREL/US U	1.9×10^1	gal
Gasoline	Gasoline, combusted in equipment NREL/US U	1.6×10^0	gal
Waste wood	Wood waste, unspecified, combusted in industrial boiler NREL/US U	5.5×10^3	lb.
Transport	Transport, lorry 3.5-16t, fleet average/US- US-EI U	7.3×10^3	ton-mi
Pentachlorophenol	LCA model	6.0×10^2	lb.
Glulam	Glued laminated timber, outdoor use, at plant/US- US-EI U	1.0×10^3	ft ³
Natural gas	Natural gas, combusted in industrial boiler NREL/US U	2.0×10^3	ft ³
Electricity	Electricity, medium voltage, at grid, 2015/US US-EI U	9.2×10^2	kWh

PENTACHLOROPHENOL-TREATMENT PROCESS

LCI data was not available for pentachlorophenol in the DATASMART LCI database, so a new process was created using data from a published study on LCA of treated utility poles (Bolin and Smith 2011). It was assumed that the yield of treated wood was 100% and the species mix was assumed to be 60% Southern pine and 40% Douglas fir with an average density of 39 pounds-per-cubic-foot (39 lb./ft³). The pentachlorophenol retention was 0.6 lb./ft³. Selected life-cycle inventory data for the pentachlorophenol chemical are listed in Table 4.9.

Table 4.9 Selected life-cycle inventory data for 1 lb. of pentachlorophenol.

Description	LCI Data Source	Quantity	Unit
Water	Water, unspecified natural origin, US	3.5 x 10 ⁰	gal
Electricity	Electricity, medium voltage, at grid, 2015/US US-EI U	3.7 x 10 ⁻¹	kWh
Natural gas	Natural gas, processed, at plant NREL/US U	3.3 x 10 ⁰	ft ³
Natural gas	Natural gas, combusted in industrial boiler NREL/US U	3.4 x 10 ⁰	ft ³
Diesel	Diesel, at refinery/I NREL/US U	1.6 x 10 ⁰	gal
Diesel	Diesel, combusted in industrial boiler NREL/US U	6.7 x 10 ⁻⁴	gal
Fuel oil	Residual fuel oil, combusted in industrial boiler NREL/US U	2.8 x 10 ⁻²	lb.
Coal	Bituminous coal, combusted in industrial boiler NREL/US U	2.2 x 10 ⁻²	lb.
Transport	Transport, lorry 3.5-16t, fleet average/US- US-EI U	2.8 x 10 ⁻²	ton-mi
Transport	Transport, train, diesel powered NREL/US U	5.3 x 10 ⁻¹	ton-mi

WELDED-PLATE ASSEMBLIES

The welded-plate assemblies were assumed to be manufactured from galvanized steel sheet with a density of 490 lb./ft³, and their sizes were calculated from the drawings provided in Appendix C of the *Development of Cost-competitive Timber Bridge Designs for Long Term Performance, Task 3A Report* (Fosnacht et al. 2018).

DIAPHRAGMS

The bridge abutment and intermediate diaphragms were assumed to be manufactured from galvanized steel sheet with a density of 490 lb./ft³, and their sizes were estimated from the drawings provided in Appendix A of the *Task 3A Report* (Fosnacht et al., 2018). The abutment diaphragms required 14 main (large) components and 28 stiffeners. The intermediate diaphragms required 21 main (large) components and 42 stiffeners. The inputs required for shaping/cutting/drilling the abutments were excluded.

STEEL SUPPORT BEAMS

Eight W30 x 108 steel beams (108 lbs./ft) were needed to manufacture the bridge. It was assumed the beams were 54.17-ft long and were manufactured from hot-rolled sheet steel with a density of 490 lb./ft³, which was then galvanized. The manufacturing yield loss was 10% by weight. Selected life-cycle inventory data for the steel support beams are listed in Table 4.10.

Table 4.10 Selected life-cycle inventory data for 18.33 kg of steel beam.

Description	LCI Data Source	Quantity	Unit
Steel	Hot rolled sheet, steel, at plant NREL/RNA U	20.2	kg
Galvanization process	Galvanization (zinc coating) of steel parts	0.787	m ²

SHEAR PLATE, DECK CLIPS, COVER PLATES, AND FLASHING

These items were assumed to be manufactured from galvanized steel sheet with a density of 490 lb./ft³. The flashing was 22-gauge (.0299-in thick) with a width of 5 in.

WATERPROOF MEMBRANES

Both the waterproof membrane for the steel cover plates and bridge/deck waterproofing membrane were assumed to be manufactured from butadiene styrene sheeting with a weight of 0.26 lb./ft². Selected life-cycle inventory data for the waterproof membrane are listed in Table 4.11.

Table 4.11 Selected life-cycle inventory data for 1 kg of waterproof membrane.

Description	LCI Data Source	Quantity	Unit
Sand	Sand (in ground)	5.3×10^{-1}	kg
Shale	Shale (in ground)	6.8×10^{-1}	kg
Pitch	Proxy Pitch 100#/CN	1.8×10^0	kg
Pitch	Proxy Pitch 10#/CN	2.1×10^{-1}	kg
Styrene butadiene styrene	Proxy_SBS/CN	2.5×10^{-1}	kg
Polyester	Proxy_Polyester materials/CN	7.9×10^{-1}	kg
Insulation	Proxy_Glass wool heat insulation/CN	2.6×10^{-1}	kg
Polyethylene	Proxy_PE film/CN	1.1×10^0	g
Transport	Transport, train, average/CN U	1.1×10^{-1}	ton-km
Transport	Transport, lorry, 2-5t, suburb, average/CN S	1.0×10^{-1}	ton-km
Coal	Hard coal supply mix/CN US-EI U	3.9×10^{-1}	kg
Electricity	Electricity mix/CN US-EI U	9.5×10^{-2}	kWh

BITUMINOUS OVERLAY

The bituminous overlay was assumed to be asphalt with a density of 145 lb./ft³. 321.62 ft³ of asphalt was required to cover the bridge; however, asphalt for the bridge approaches was excluded from the study. Selected life-cycle inventory data for the bituminous overlay are listed in Table 4.12.

Table 4.12 Selected life-cycle inventory data for 1 kg of bituminous overlay (mastic asphalt).

Description	LCI Data Source	Quantity	Unit
Bitumen	Bitumen, at refinery/US* US-EI U	8.0×10^{-2}	kg
Diesel	Diesel, burned in building machine/GLO US-EI U	2.2×10^{-2}	MJ
Electricity	Electricity, medium voltage, at grid/CH* US-EI U	2.8×10^{-2}	kWh
Heat	Heat, light fuel oil, at industrial furnace 1MW/US* US-EI U	1.5×10^0	MJ
Limestone	Limestone, milled, packed, at plant/US* US-EI U	2.6×10^{-1}	kg
Sand	Sand, at mine/US* US-EI U	6.6×10^{-1}	kg
Transport	Transport, freight, rail/US- US-EI U	1.6×10^{-2}	ton-km
Transport	Transport, lorry 20-28t, fleet average/US* US-EI U	5.4×10^{-2}	ton-km

OTHER

It was assumed each railing post cap weighed 1 lb. and was manufactured from rigid polypropylene and the rubber spacers were manufactured from 0.125-in-thick synthetic rubber with a density of 0.0311 lb./in³. All bolts, nuts, washers, and nails were manufactured from galvanized low-alloyed steel; the weight of individual pieces was estimated using the Bolt Weight Calculator (<https://www.portlandbolt.com/technical/tools/bolt-weight-calculator/>).

4.4.9 Electricity Mixes

The electricity usage was modeled using the 2015 average US electricity grid process from the DATASmart LCI database (LTS 2019a). (These values are taken from 2015 US Energy Information Administration (EIA) data.) The electricity grid mix is a mix of domestic production from various sources, and the average grid mix for the electricity datasets used in this study is shown in Table 4.13.

Table 4.13 Average electricity grid mix for the US

Electricity source	2015
Hard coal	33.17%
Oil	0.69%
Natural gas	32.70 % (47% shale)
Industrial gas	0.16%
Petroleum coke	0.16%
Nuclear	19.55%
Hydro	6.11%
Cogen	0.103%
Geothermal	0.39%
Solar PV	0.61%
Wind	4.68%
Canadian imports	0.31%
Mexican imports	0.03%

4.4.10 Data Quality

The quality of the data used in this preliminary LCA is reasonably accurate and representative of the processes modeled. However, Data Quality Requirements and Indicators (DQI) have not been assigned to this study. (This includes evaluation of data reliability, completeness, geographical correlations, further technological correlation, and sample size using the Pedigree Matrix (Weidema and Wesnaes, 1996; Frischknecht et al., 2004).)

4.4.11 Results of Life-Cycle Impact Assessment

The following sections summarize the key characterized results of the LCA including contribution analyses.

4.4.11.1 Bridge Life Cycle

Table 4.14 presents the life-cycle impacts for the completed SLC 516 bridge.

Table 4.14 Life-cycle impacts of the SLC 516 bridge using the LTS 2019 method (LTS, 2019b).

Damage Category	Unit	SLC 516 Bridge
Human Health	DALY	0.836
Ecosystems	species*yr	7.10×10^{-4}
Resources	\$	7.97×10^3
Cumulative Energy Demand	MJ	1.92×10^6
Climate Change	kg CO ₂ eq.	1.05×10^5
Water Use	m ³	654

4.4.11.2 Contribution Analysis

Contribution analyses identify the environmental hot-spots within the bridge system, which are the processes that contribute disproportionately to the overall life-cycle impacts of the system. The identification of hot-spots provides a deeper understanding of what is driving the environmental performance of the completed bridge and allows for the identification of opportunities for process improvement. The contribution analysis for the completed bridge is shown in Figure 4.81.

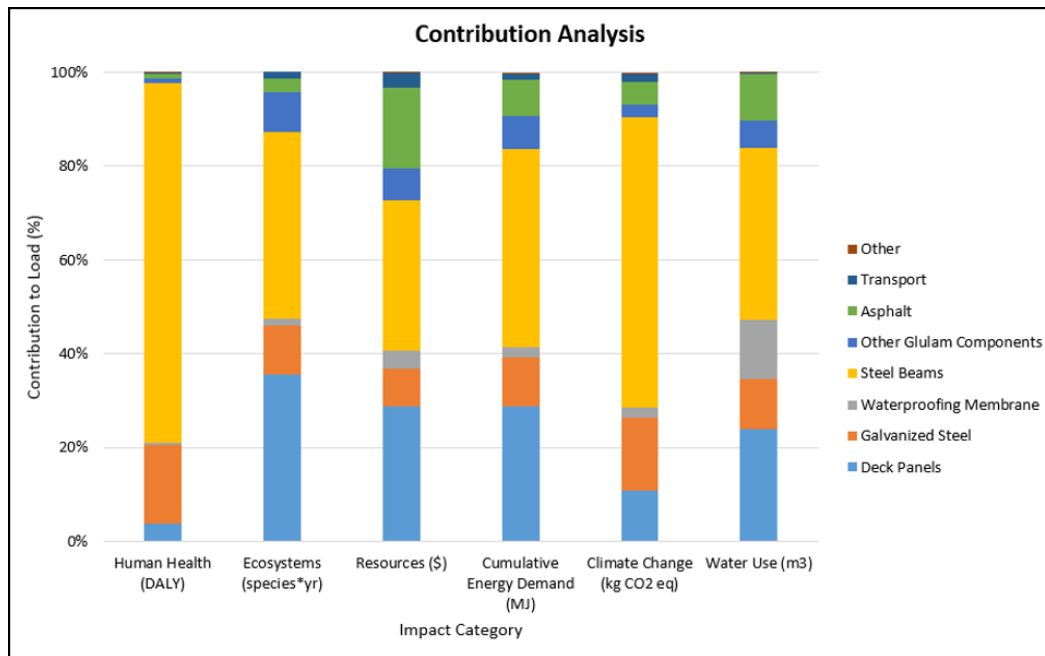


Figure 4.81 Contribution analysis for the completed SLC 516 bridge using the LTS 2019 method (LTS, 2019b).

As shown, production of the steel beam supports accounts for a large portion of the total impact in each impact category, contributing 77%, 40%, 32%, 42%, 62%, and 37% of the impacts in the Human Health, Ecosystems, Resources, Cumulative Energy Demand, Climate Change, and Water Use impact categories, respectively. The next largest contributor to the total impacts was the glulam deck panels, contributing 36%, 29%, 29%, and 24% of the impacts in the Ecosystems, Resources, Cumulative Energy Demand, and Water Use impact categories, respectively. The next largest contributor to overall impacts were the galvanized steel components (which excludes the steel beams), accounting for 17%, 10%, 10%, 16%, and 11% of the impacts in the Human Health, Ecosystems, Cumulative Energy Demand, Climate Change, and Water Use impact categories. The asphalt contributed between 1% and 17% of the impacts overall, with the highest total (17%) in the Resources impact category. The manufacture of the glulam stiffeners, posts, and rails (“Other Glulam Components”) contributed a relatively minor amount to total impacts in all impact categories.

4.4.12 Life-Cycle Assessment Conclusion

The objective of the study was to understand the environmental impacts of the SLC 516 bridge on a cradle-to-gate basis. The steel beam supports account for the largest portion of total impacts in each impact category, ranging from 32% to 77%, while the glulam deck panels contribute 24% to 36% of the impacts in four of the six impact categories. The galvanized steel components and asphalt contribute an average of 12% and 7% of the impacts in each impact category, respectively.

CHAPTER 5: HENNEPIN COUNTY TIMBER BRIDGE CONSTRUCTION PROJECT

Based on the products from project tasks 1 and 2, potential MnDOT and county partners were identified for planning and construction of up to three beam or slab type bridges. A decision was subsequently made to complete two demonstration projects. In Task 3B, the project team partnered with Hennepin County, Minnesota on the design, construction and validation of a bridge that was constructed in the city of Dayton, Minnesota. This bridge was constructed by a Redstone Construction, LLC construction crew using a dowel-laminated timber deck using metal spikes. The research team worked with Hennepin County to track design, bidding, cost, and construction of the bridge. Funds from the project were not used for construction.

5.1 BACKGROUND

The new Hennepin County Bridge selected for this project is state bridge number 27C53, which replaced bridge L8081. It is located on County State Aid Highway 202 (Elm Creek Road) and crosses the Elm Creek River. It is a relatively low volume road with average daily traffic of 800 vehicles (2018). The original bridge superstructure was a longitudinal steel girder with transverse plank deck. Figures 5.1 to 5.6 show the bridge prior to removal. Figure 5.7 shows the location of the bridge. Appendix E contains the September 2018 Minnesota Structure Inventory Report for Bridge L8081. While the document shows it was constructed in 1973, it is likely that some of the piling and structural components may have been reutilized. The inventory report indicated that bridge condition required significant repairs or replacement after years in-service. In addition, the bridge was a single-lane bridge that did not safely meet the needs of the public motorists and encroached upon the natural stream conditions.

Funding for the construction of the project was provided by Hennepin County, Minnesota. The site work and construction were completed by Redstone Construction, LLC. The project team included Hennepin County, University of Minnesota Duluth Natural Resources Research Institute, US Forest Service Forest Products Laboratory, LHB Engineering and Iowa State University.

5.2 OBJECTIVE AND SCOPE

The objective of this task was to identify, design and construct a demonstration bridge using standard timber design options and to develop and incorporate design details focused on long-term performance and durability. The focus was a longitudinal dowel laminated deck with steel spikes superstructure which is a pre-fabricated panelized bridge system which reduced bridge construction times. On-site photo and time documentation were also completed for the construction. The project team collaborated with Hennepin County and other partners to demonstrate and validate the cost parameters associated with the project and compare them to preconstruction estimates. A life-cycle assessment was also completed based on the final superstructure design specifications for the bridge constructed. Finally, a detailed project report was completed that could be used to capture lessons

learned during the construction phase of the project. Research funds were not used for bridge construction.



Figure 5.1 Original steel girder bridge (L8081) that was replaced during this project.



Figure 5.2 Elm Creek Road and Hennepin County Bridge L8081 prior to removal



Figure 5.3 Superstructure condition for Hennepin County Bridge L8081.



Figure 5.4 Deteriorated steel girders in underside view of the superstructure for Hennepin County Bridge L8081.



Figure 5.5 Close up of steel girder bearing on timber pile and cap abutment for bridge L8081.



Figure 5.6 Transverse timber plank deck and steel railing system for bridge L8081.

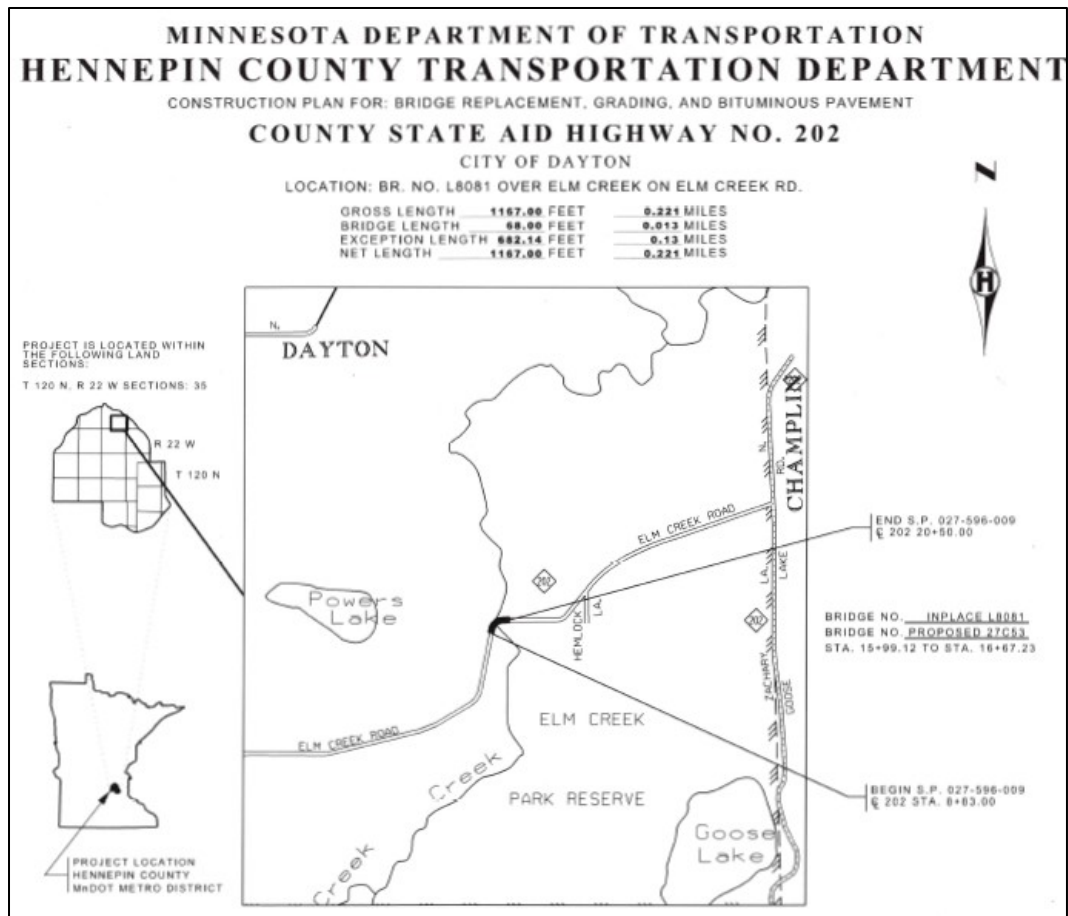


Figure 5.7 Geographic information about the site location of the project bridge.

5.3 DESIGN, BID AND CONSTRUCTION

The design, contractual, and construction processes for Hennepin County bridge number 27C53 (replacement for bridge number L8081) involved efforts from several agencies and organizations. An overview of the design, contractual bid process, and construction of the bridge follows.

5.3.1 Design

The overall project construction plan for bridge replacement, grading and bituminous pavement was developed by Hennepin County Public Works Department (Minnesota), and is included at Appendix E. The project construction plan includes the title sheet, general layout, statement of estimated quantities, earthwork tabulations and standard plates, quantity tabulations, public utility plan and tabulations, typical sections, standard plan sheets, alignment plan and tabulations, removal plan, construction plan, profiles, super elevation and turf establishment, stormwater pollution prevention plan, erosion control plan, cross-section match line, cross-sections, traffic control plan, striping and signing plan and bridge plan.

The 2018 edition of the MnDOT Standard Specifications for Highway Construction and all supplements governed the specifications ([MnDOT, 2018](#)). Detailed specifications for this project are in a document referred to as "Division SB," which is included at Appendix E. The Division SB document includes the following: bridge plans, plans and working drawings, restrictions on movement and storage of heavy loads and equipment, employee health and welfare, removal of asbestos and regulated waste, bridge and abutment construction, steel bridge construction, timber bridge construction, removal of existing bridge, structural excavations and backfills, piling, riprap, steel shells for concrete piling and fasteners.

The structural design for the bridge was done in accordance with the American Association of State Highway and Transportation Officials (AASHTO), LRFD Bridge Design Specifications for Highway Bridges (2017). The bridge design was comprised of a longitudinal dowel-laminated timber deck with metal spikes and was designed for the design criteria:

- Live load HL-93
- Dead load (timber 50 pounds per cubic foot (PCF) / wearing surface 140 PCF)
- Design speed = 35 miles per hour (MPH)
- The tabulated design properties were:
 - $F_b = 1.00$ ksi prefab panels for spans 1, 2, and 3 (Douglas-fir larch No 1).
 - $F_b = 1.20$ ksi pile caps (Douglas-fir larch No 1).
 - $F_b = 1.75$ ksi rail posts (Douglas-fir larch dense select structural).
 - $F_b = 1.20$ ksi for all other timber.
 - $F_v = 0.18$ ksi
 - $F_{c-perp} = 0.625$ ksi
 - Live load deflection criteria – $L/300$ for the strip width and $L/425$ for the final structure
- The structural steel design properties were:
 - $F_y = 36$ ksi specification 3306
- The reinforced concrete design properties were:
 - $f'_c = 4$ ksi and $F_y = 60$ ksi

The Hennepin County construction bridge construction plan and Division SB (Appendix B and C) specified the following for the bridge, materials and fabrication associated with the timber bridge superstructure and rail construction:

1. Construction requirements shall conform to specification 2403.3.
2. All timber is to be pressure treated per specification 3491 and the special provisions. All timber in the bridge shall be treated with copper naphthenate, or other oil-based treatment as approved by the engineer, in accordance with specification 3491 and the current American Wood Preservers Association (AWPA) Standards, according to best management practices.
3. All hardware is to be galvanized per specification 3392.
4. Steel indicated in the plans was to be galvanized per specification 3394.
5. Thread on all bolts to be upset after installation.
6. All timber is to be rough unless otherwise noted.

7. The spike laminated deck panel and glue laminated crash rail shall be shop drilled and treated to minimize field treatment. All timber cut or drilled in the field shall be treated per specification 2403.3E.
8. All timber fabrication to be detailed on shop drawings. Shop drawings shall be submitted to the sealing engineer for approval prior to shipping materials.
9. Glue laminated rail construction requirements. This work shall consist of the fabrication and installation of glued laminated rails and shall be performed in accordance with the provisions of 2403.3 and the following:
 - a. All applicable provisions of 2403.3.N.2 shall apply to glued laminated rail.
 - b. Hardware that attaches the bridge railing to the dowel-laminated deck shall be hand tightened only during cold weather and the contractor will refrain from upsetting the hardware at this time. The contractor shall then tighten the fasteners at the Engineer's direction once weather permits and upset the hardware at the final torque.
 - c. Plastic caps shall be installed on the top of each timber post. The caps shall be purpose built to timber bridge rails to prevent moisture entering the end grain. Protective plastic caps shall be incidental to the glue-laminated rail. The caps shall be black in color.
10. Timber deck expansion material. Contractor to install cork or neoprene padding material that is a minimum of 1/4 in thick between timber material and steel L brackets located on the top of each abutment and pier. The cost of installation and material shall be incidental to the glued laminated deck, Item No. 2403.618.
11. Timber deck flashing material. Contractor to install 26-gauge (minimum) galvanized flashing material on the south edge of the bridge deck for the entire length as noted in the plans. The flashing shall extend a minimum of 3 in off the deck to assure rain does not run down the end grain. Vertical flashing shall be installed on all timber curb members to protect each scupper block on the south edge. The cost of installation and material shall be incidental to the glued laminated deck, Item No. 2403.618.

Figure 5.8 shows the perspective photograph of the completed bridge superstructure. The design features longitudinal nail-laminated panels, transverse spreader beams, and the guard rail system. Selected views for these details are shown in Figures 5.8 to 5.19. Additional and significant detail for all timber components, their installation, connections and other is present in the Construction Plan (Appendix E).



Figure 5.8 Completed picture of dowel-laminated deck with metal spikes, transverse spreader beams (highlighted with red arrow), and railings.

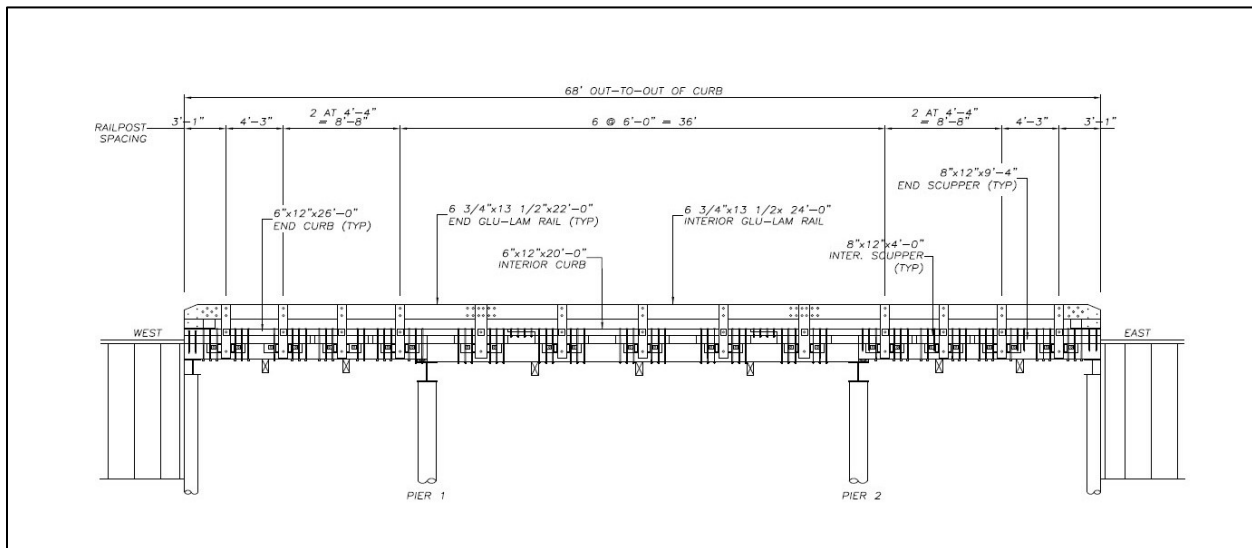


Figure 5.9 Elevation view of Hennepin County bridge 27C53.

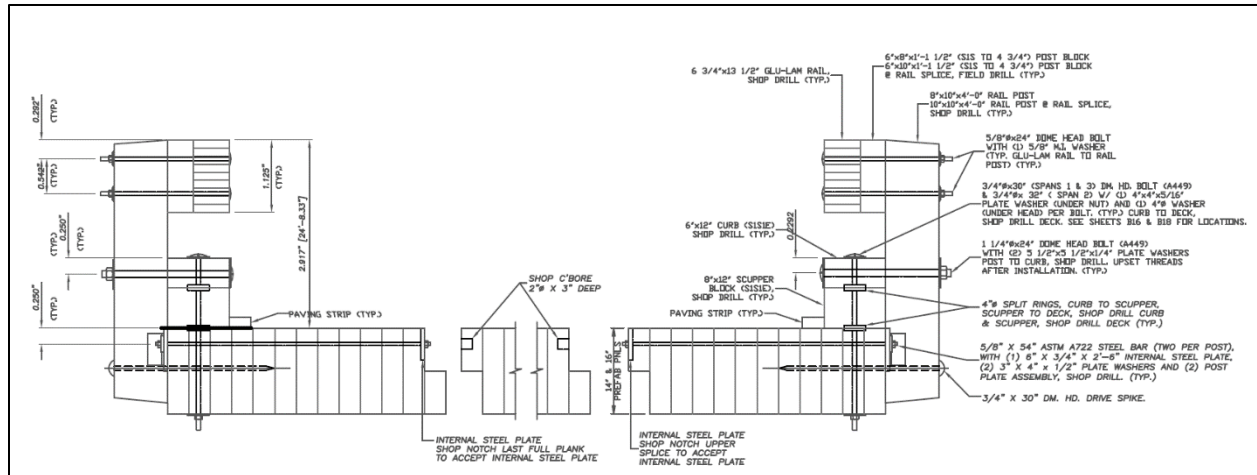


Figure 5.10 Transverse cross-section view showing dowel-laminated timber deck with metal spikes, and crash-tested bridge railing and curb system.

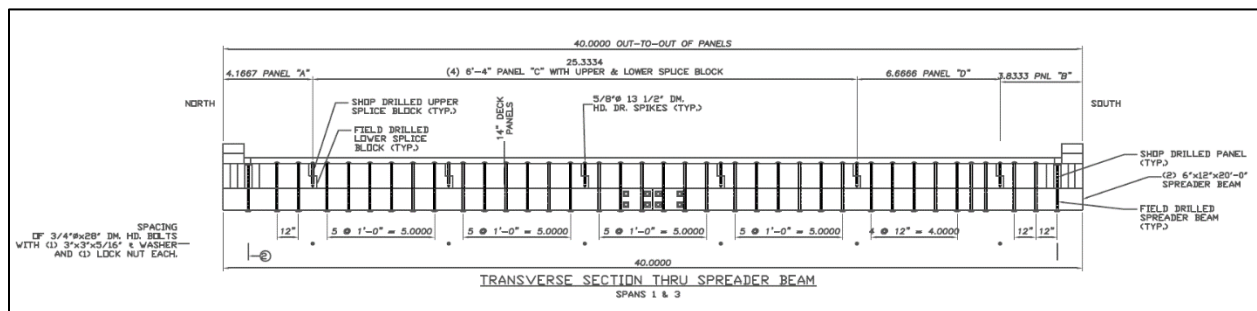


Figure 5.11 Transverse section view showing the transverse spreader beam connection details for end spans 1 and 3.

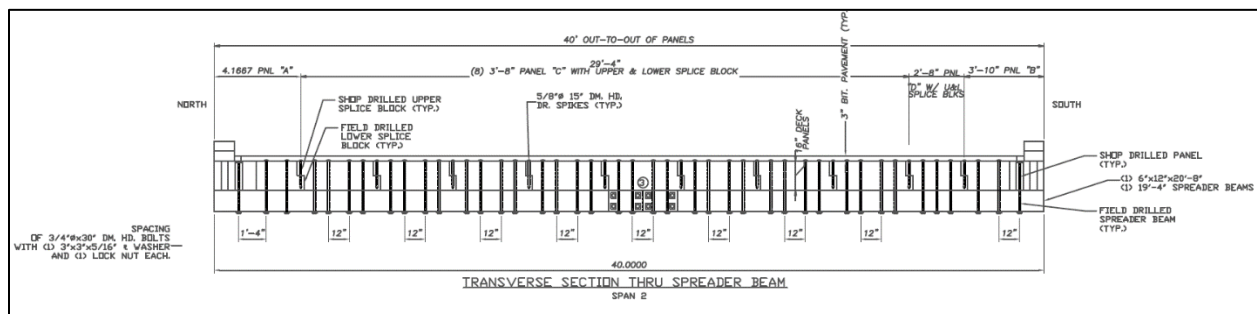


Figure 5.12 Transverse section view showing the transverse spreader beam connection details for span 2.

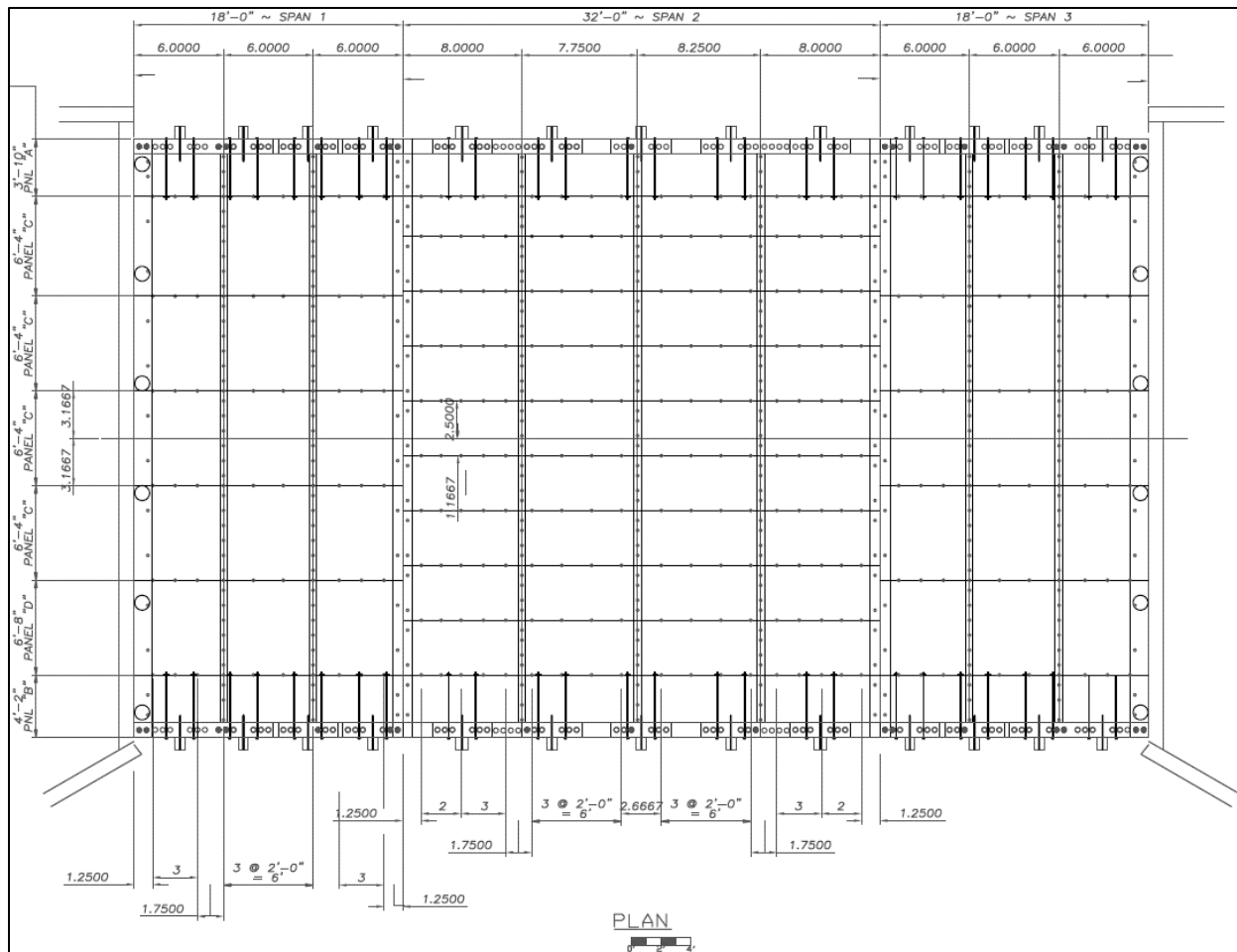


Figure 5.13 Plan view showing dowel-laminated timber deck with metal spikes, general configuration.

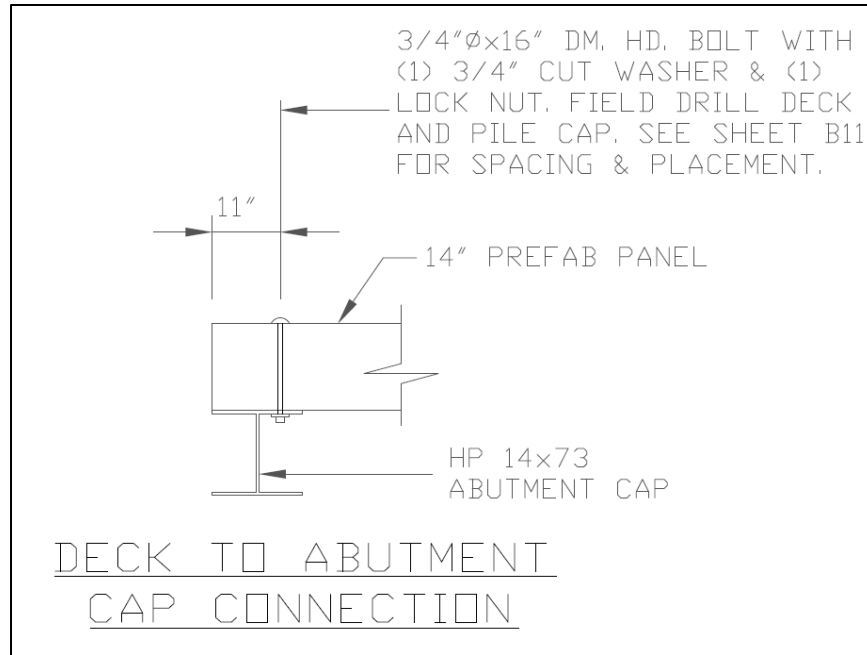


Figure 5.14 Connection details for the wood deck at the steel H-beam.

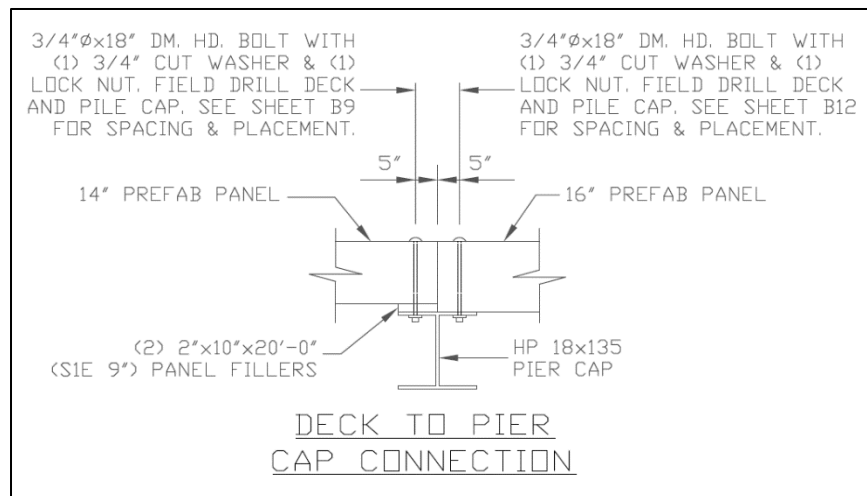


Figure 5.15 Connection detail for end-butted wood decks at the steel.

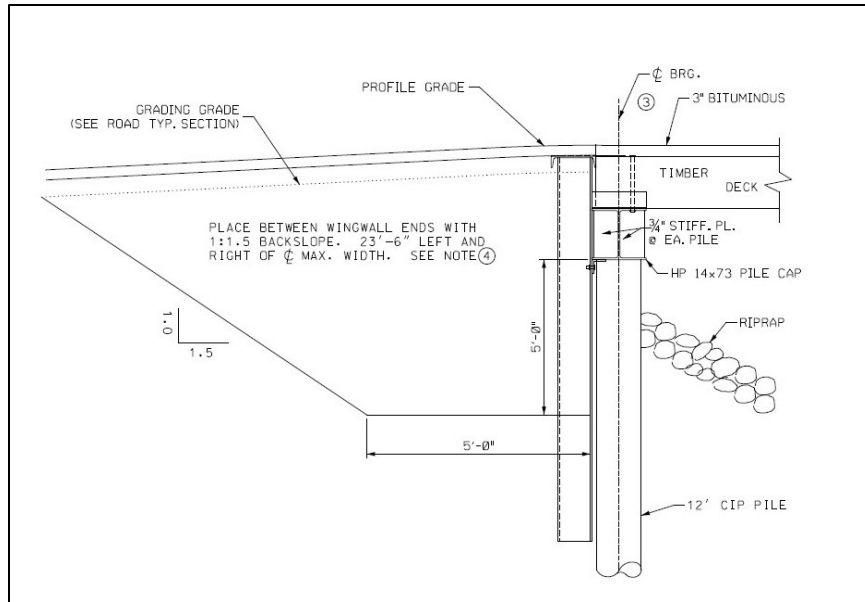


Figure 5.16 Profile view of abutment corner detail.

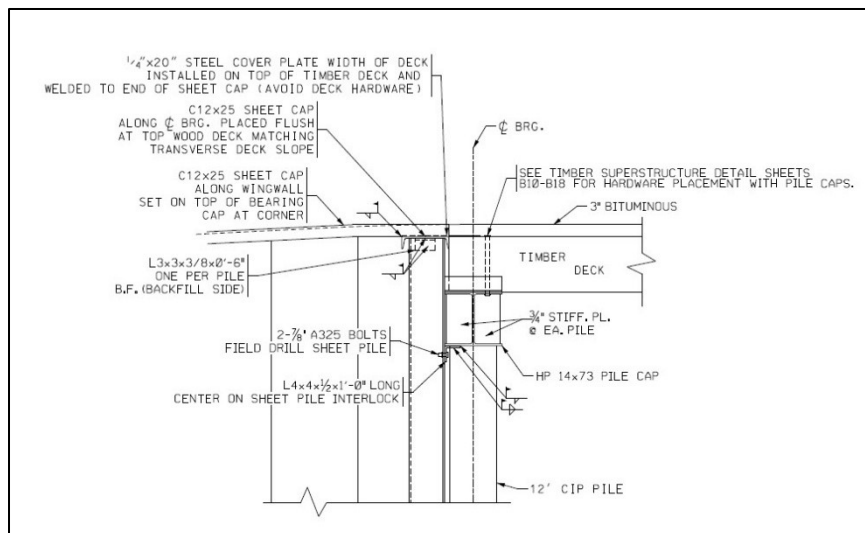


Figure 5.17 Profile view of abutment.

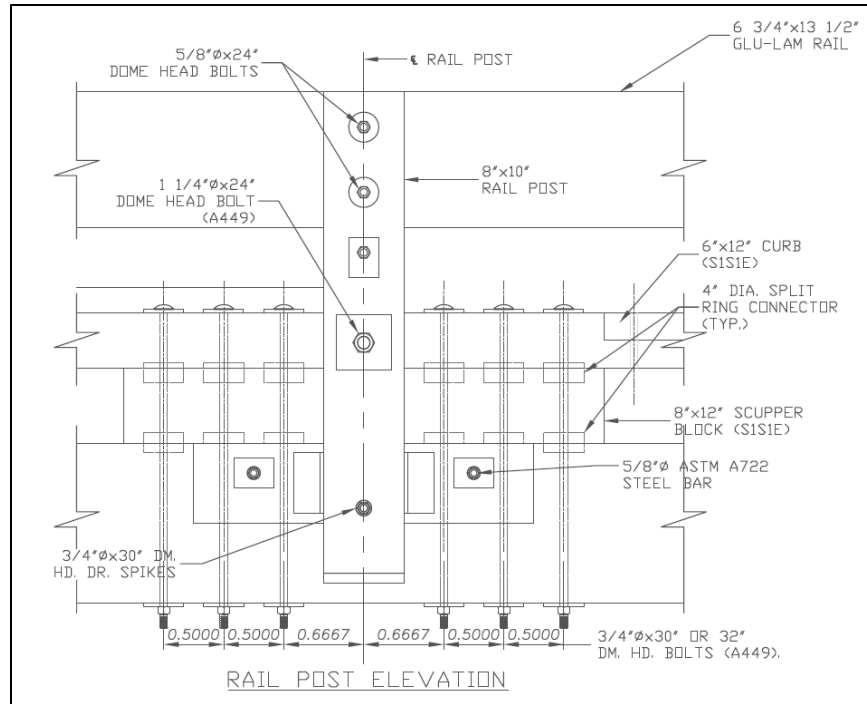


Figure 5.18 Elevation view of typical steel hardware for each bridge rail post location and revealing the hidden split-ring connectors and thru-bolts which interconnect the curb and rail system to the dowel lam deck. (Test Level 4 – NCHRP350)

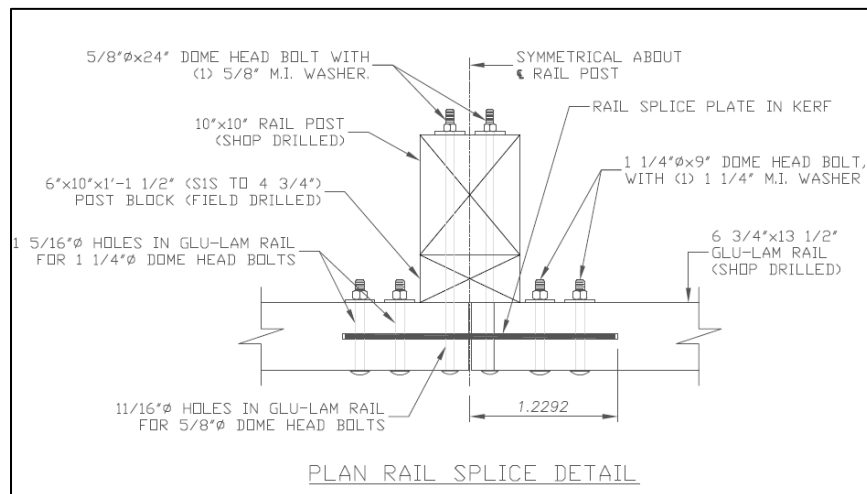


Figure 5.19 Plan view of the splice detail for the end-buttet glulam rail members.

5.3.2 Bid Process and Materials

Based on the design specifications, Hennepin County solicited bids from outside vendors for bridge removal, constuction, grading and bituminous pavement. The bid process opened on August 31, 2018 and closed on September 25, 2018. Key information on the bid project are located at: <https://egram.co.hennepin.mn.us/default.php?WorkOrderId=131>. This location includes the project advertisement, plans and all addendum, project bid abstract, and project bid summary.

Five bids were received for this project. The low bid for the complete project was \$1,396,584.80 and the high bid was \$1,641,666.62. The low bid was 20.19% below the engineer's estimate. Redstone Construction LLC submitted the low bid and was awarded the contract for the project. This project included removal of bridge L8081 and significant construction to increase the bridge and roadway dimensions for the project. Within the project bid abstract, Table 5.1 shows the bid costs received from Redstone Construction were associated with the wood construction. Appendix E shows the complete project bid abstract received from each of the five companies.

Table 5.1 Bid proposal selected for the bridge construction project.

Item No.	Item	Units	Quantity	Unit Price	Total Price
2021.501	Mobilization	Lump sum	1	\$158,000.00	\$158,000.00
2031.502	Field Office Type D	Each	1	\$15,000.00	\$15,000.00
2101.501	Clearing & Grubbing	Lump sum	1	\$9,000.00	\$9,000.00
2104.502	Remove Sign Type C	Each	18	\$35.00	\$630.00
2104.503	Remove Guardrail	Lineal feet	190	\$10.00	\$1,900.00
2104.503	Remove Metal Culvert	Lineal feet	170	\$9.00	\$1,530.00
2104.503	Sawing Bituminous Pavement	Lineal feet	47	\$2.25	\$105.75
2104.504	Remove Bituminous Pavement (P)	Square yard	3,104	\$3.75	\$11,640.00
2104.601	Remove Regulated Waste Material (Bridge)	Lump sum	1	\$2,450.00	\$2,450.00
2105.504	Geotextile Fabric Type 6	Square yard	5,190	\$2.50	\$12,975.00
2105.509	Stabilizing Aggregate	Ton	100	\$40.00	\$4,000.00
2106.507	Common Embankment (Cv) (P)	Cubic yard	1,016	\$14.00	\$14,224.00
2106.507	Excavation - Common (P)	Cubic yard	1,680	\$18.50	\$31,080.00
2118.509	Aggregate Surfacing Class 2	Ton	196	\$54.00	\$10,584.00
2123.61	Street Sweeper (With Pickup Broom)	Hour	20	\$130.00	\$2,600.00
2130.523	Water	Gallon (1000)	6	\$250.00	\$1,500.00
2131.506	Calcium Chloride Solution	Gallon	185	\$5.00	\$925.00
2211.509	Aggregate Base Class 5 (P)	Ton	1,483	\$32.50	\$48,197.50
2360.509	Type Sp 12.5 Wearing Course Mix (3;C)	Ton	933	\$87.00	\$81,171.00
2401.601	Structure Excavation	Lump sum	1	\$25,000.00	\$25,000.00
2402.508	Structural Steel (3309) (P)	Pound	23,038	\$3.25	\$74,873.50

Item No.	Item	Units	Quantity	Unit Price	Total Price
2403.603	Timber Railing (P)	Lineal feet	136	\$350.00	\$47,600.00
2403.618	Glued Laminated Deck Panels (P)	Square feet	2,720	\$105.00	\$285,600.00
2442.501	Remove Existing Bridge	Lump sum	1	\$30,000.00	\$30,000.00
2452.502	Pile Points 16"	Each	16	\$345.00	\$5,520.00
2452.502	C-I-P Conc Test Pile 85 Ft Long 12" (P)	Each	2	\$10,000.00	\$20,000.00
2452.502	Pile Redriving	Each	32	\$250.00	\$8,000.00
2452.502	C-I-P Conc Test Pile 85 Ft Long 16" (P)	Each	2	\$12,000.00	\$24,000.00
2452.502	Pile Points 12"	Each	16	\$240.00	\$3,840.00
2452.502	Pile Analysis	Each	2	\$2,200.00	\$4,400.00
2452.603	C-I-P Concrete Piling 16"	Lineal feet	1,190	\$55.00	\$65,450.00
2452.603	C-I-P Concrete Piling 12"	Lineal feet	1,190	\$40.00	\$47,600.00
2452.618	Steel Sheet Piling (P)	Square feet	2,430	\$36.00	\$87,480.00
2501.502	28" Span Cas Pipe-Arch Apron	Each	2	\$2,000.00	\$4,000.00
2501.502	18" Rc Pipe Apron	Each	2	\$1,500.00	\$3,000.00
2501.502	24" Rc Pipe Apron	Each	4	\$1,850.00	\$7,400.00
2501.503	18" Rc Pipe Culvert Des 3006 Cl Iii	Lineal feet	52	\$76.00	\$3,952.00
2501.503	24" Rc Pipe Culvert Class Iii	Lineal feet	96	\$82.50	\$7,920.00
2501.603	28" Span Pipe-Arch Culvert	Lineal feet	44	\$140.00	\$6,160.00
2502.502	4" Precast Concrete Headwall	Each	4	\$375.00	\$1,500.00
2502.503	4" Perf Tp Pipe Drain	Lineal feet	1,000	\$13.00	\$13,000.00
2511.504	Geotextile Filter Type 7	Square yard	1,050	\$2.75	\$2,887.50
2511.507	Random Riprap Class Iv	Cubic yard	830	\$80.00	\$66,400.00
2533.503	Portable Precast Conc Barrier Des 8337	Lineal feet	50	\$30.00	\$1,500.00
2554.502	End Treatment-Energy Absorbing Terminal	Each	1	\$3,500.00	\$3,500.00
2554.502	Anchorage Assembly - Type 31	Each	3	\$1,500.00	\$4,500.00
2554.503	Traffic Barrier Design Type 31	Lineal feet	491	\$25.00	\$12,275.00
2554.503	Traffic Barrier Design Trans Type 31	Lineal feet	100	\$130.00	\$13,000.00
2563.601	Traffic Control	Lump sum	1	\$27,500.00	\$27,500.00
2563.601	Traffic Control Supervisor	Lump sum	1	\$3,400.00	\$3,400.00
2563.613	Portable Changeable Message Sign	Unit day	40	\$50.00	\$2,000.00
2564.518	Sign Panels Type C	Square feet	36.3	\$60.00	\$2,178.00
2572.503	Temporary Fence	Lineal feet	500	\$3.00	\$1,500.00
2573.501	Erosion Control Supervisor	Lump sum	1	\$1,500.00	\$1,500.00
2573.502	Storm Drain Inlet Protection	Each	4	\$200.00	\$800.00
2573.503	Silt Fence; Type Ms	Lineal feet	820	\$5.25	\$4,305.00
2573.503	Silt Fence; Type Sd	Lineal feet	250	\$25.00	\$6,250.00
2573.503	Silt Fence; Type Hi	Lineal feet	1,540	\$6.75	\$10,395.00

Item No.	Item	Units	Quantity	Unit Price	Total Price
2573.503	Flotation Silt Curtain Type Moving Water	Lineal feet	448	\$36.50	\$16,352.00
2573.51	Sediment Removal Backhoe	Hour	10	\$145.00	\$1,450.00
2574.507	Compost Grade 3	Cubic yard	175	\$100.00	\$17,500.00
2574.508	Fertilizer Type 4	Pound	100	\$1.00	\$100.00
2575.504	Erosion Control Blankets Category 3n	Square yard	2,615	\$1.95	\$5,099.25
2575.504	Rapid Stabilization Method 4	Square yard	2,787	\$2.00	\$5,574.00
2575.508	Seed Mixture 35-241	Pound	30	\$20.00	\$600.00
2582.503	4" Dble Solid Line Multi Comp Gr In	Lineal feet	1,170	\$1.89	\$2,211.30
Contract Total:					\$1,396,584.80

5.3.2.1 Timber and Timber Hardware

The timber panels used in this project were dowel-laminated timber panels and manufactured by Wheeler Consolidated. More information about the company and product family is located at <http://www.wheeler-con.com/highway-bridges/panel-lam-timber-vehicle-bridges/>. The products supplied for this project were fabricated using individual solid-sawn Douglas fir structural timbers that were 4 in wide and the required depth for each panel. These individual timbers were pressure-treated using copper naphthenate wood preservative and then shop assembled with steel dowels (spikes) into panels. For this project, the dowels were 3/8 in diameter (\varnothing) x 15 in nails and 3/8 in \varnothing x 11 in nails for the splice joints (shiplap) blocks. The pattern of the dowels and the deck thickness were a function of the span length and the design load. The dowels were positioned in two rows near the top and the bottom and spaced approximately one foot apart. Lumber laminations were added two at a time until the panel width was achieved. Penetrating four lumber laminations, the dowel pattern was staggered and repeated to avoid driving dowels into each other (Wheeler Consolidated, 2019). For the railings, glue-laminated beams were obtained, predrilled for hardware and preservative treated. Following fabrication, panels and hardware are loaded on a construction truck and delivered to the job site for staging prior to construction. Table 5.2 shows the wood material list and Table 5.3 shows the hardware material list for the timber components of the bridge project.

Table 5.2 Wood material list for the project.

	Description	Quantity	Size	Length
Prefabricated Wood Panels	Type A18	2	1 ft 2 in by 4 ft 0 in	18 ft
	Type B18	2	1 ft 2 in by 3 ft 8 in	18 ft
	Type C18	8	1 ft 2 in by 6 ft 0 in	18 ft
	Type D18	2	1 ft 2 in by 6 ft 4 in	18 ft
	Type A32	1	1 ft 4 in by 4 ft 0 in	32 ft
	Type B32	1	1 ft 4 in by 2 ft 4 in	32 ft
	Type C32	8	1 ft 4 in by 3 ft 8 in	32 ft
	Type D32	2	1 ft 4 in by 3 ft 4 in	32 ft
Glue-laminated Timber Railing	End Rail	4	10 ¾ in by 6 in	22 ft
	Inner Rail	2	10 ¾ in by 6 in	24 ft
Spreader Beam	Rough Sawn	8	6 in by 12 in	20 ft
	Rough Sawn	3	6 in by 12 in	20 ft 8 in
	Rough Sawn	3	6 in by 12 in	19 ft 4 in
Spreader Beam Splice	Rough Sawn	8	3 in by 12 in	3 ft by 0
	Rough Sawn	6	3 in by 12 in	3 ft 4 in
Panel Filler at Pier	Smooth 1 Edge (S1E)	4	2 in by 10 in (S1E to 9 in)	20 ft
Rail Post	Rough Sawn	22	8 in by 10 in	4 ft 0 in
Rail Post Block	Smooth 1 Side (S1S)	14	6 in by 8 in (S1S to 4.75 in)	1 ft 1.5 in
Upper end Post Block	Smooth 1 Side smooth 1 Edge (S1S1E)	4	6 in by 14 in (S1S1E to 4.75 in by 13.5 in)	4 ft 11 in
Curb Transition block	S1S1E	4	8 in by 8 in (S1S1E)	2 ft 3 in
Rail Post	Rough Sawn	4	10 in by 10 in	4 ft
Rail Post Block	S1S	4	6 in by 10 in (S1S to 4.75 in)	1 ft 1.5 in
Curb – End	S1S1E	4	6 in by 12 in	26 ft
Curb – Interior	S1S1E	2	6 in by 12 in	20 ft
Scupper – End	S1S1E	4	8 in by 12 in	9 ft 4 in
Scupper – Interior	S1S1E	18	8 in by 12 in	4 ft
Edge Strip	Rough Sawn	17	3 in by 4 in	8 ft

Note: Dimensions for the prefabricated panels are for the full depth laminates and does not include the width of the 4-in ship-lap splice block.

Table 5.3 Hardware material list for the bridge superstructure.

Item	Quantity	Weight / Each (lbs.)
3/4 in Ø by 20 in hex lags (A449) – curb to panel	34	2.40
5/8 in Ø by 13.5 in DM HD DR spike – panel splice	120	1.40
5/8 in Ø by 15 in DM HD DR spike – panel splice	180	1.52
3/4 in Ø by 16 in DM HD Bolt – Panel to abutment	28	2.80
3/4 in Ø by 18 in DM HD Bolt – Panel to pier	72	3.04
3/4 in Ø by 30 in DM HD DR Spike – Post to panel	26	3.89
5/8 in Ø by 24 in DM HD Bolt – Rail to post	60	2.49
7/8 in Ø by 9 in DM HD Bolt – Rail transition	24	.30
1.25 in Ø by 9 DM HD Bolt - Rail splice	32	6.81
¾ in Ø by 28 in DM HD Bolt – Spreader beam	148	4.24
¾ in Ø by 30 in DM HD Bolt – Spreader beam	123	4.48
¾ in Ø by 32 in DM HD Bolt (A449) – Curb to panel	54	5.48
¾ in Ø by 30 in DM HD Bolt (A449) – Curb to panel	76	4.40
¾ in Ø by 8 in DM HD Bolt – Curb Splice	16	1.84
1.25 in Ø by 24 in DM HD Bolt (A449) - Post to curb	26	11.96
60d Nails		
7/8 in MI Washers	24	0.60
4 in diameter Washers - (3/4 in Ø bolts)	164	0.94
3 in by 3 in by 5/16 in Washers - (3/4 in Ø bolts)	271	0.85
4 in by 4 in by 5/16 in Washers - (3/4 in Ø bolts)	146	1.50
3/4 in Lock washers - (3/4 in Ø bolts)	371	0.20
4 in Split ring connectors	328	0.70
5.5 in by 5.5 in by ¼ in Washers - (1.25 in Ø bolts)	52	2.28
¾ in Cut washers - (3/4 in Ø bolts)	100	0.12
3 in by 4.5 in by ½ in washers - (5/8 in Ø steel bar)	52	1.81
5/8 in MI Washers	60	0.22
1/25 in MI washers	32	1.54
5/8 in Ø by 54 in A722 Steel bar with 2 nuts	52	6.00

Note: Ø is the accepted symbol for diameter

DM HD = dome head; DR = drive

Additional materials were ordered and are shown in Table 5.4. This included a steel plate for covering the gap between the abutment and the glulam deck and a waterproof membrane to cover the steel plate. This also includes bituminous overlay (SP Type 12.5 Wearing Course Mix) and a bituminous membrane that would serve as a reinforcing and waterproof layer between the two layers of bituminous. A galvanized flashing was applied to the exterior edges of the lower side of the dowel-laminated deck to direct water away from the edge of the timber railing and panels. It consisted of a flat flashing placed under the scupper block and on top of the dowel-laminated deck panels, extending at least 3 inches beyond the edge of the bridge deck. Further, individual flashing pieces were placed into the scupper opening to protect the scupper block end grain at the opening. Additional details and photographs are shown in the construction section of the report.

Table 5.4 Materials for timber bridge superstructure.

Material	Supplier	Detail
Steel cover plate	Local sourced	1/4 in by 20 in by 38 ft, galvanized
Bridge and deck waterproofing membrane	Manufacturer: Miratek Mirafi	Each roll was 3 ft by 50 ft by 2.0 mm (79 mil) thickness.
Railing post cap	Laminated Concepts, Inc. (Big Flats, NY)	Plastic caps for rail posts to deflect water with screws
Copper naphthenate	Wheeler Consolidated (Whitewood, SD)	Preservative treatment for any on-site holes and cuts

5.3.3 Construction

The focus of this project was the timber bridge superstructure. Significant detail on the timber superstructure will be provided, with lesser detail on the cast-in-place (CIP) piling installation, abutment sheet piling, or abutment and steel H-beam pier caps. For more information on the steel installation beyond what is provided in the report, please contact the Hennepin County report authors.

5.3.3.1 Bridge Removal

The existing bridge was deconstructed and removed by Redstone Construction personnel during December 2018 and January 2019. Significant site preparation was then completed to increase the width of the bridge from one lane to two lanes and to increase the road and ditch widths. Figure 5.20 shows the bridge during deconstruction. Figure 5.21 shows the removal plan and the extent of the site construction. Figure 5.22 in Appendix B show the overlay of the new bridge dimension overlaid with the location of the original bridge.



Figure 5.20 Bridge L8081 during demolition. Photo credit Hennepin County.

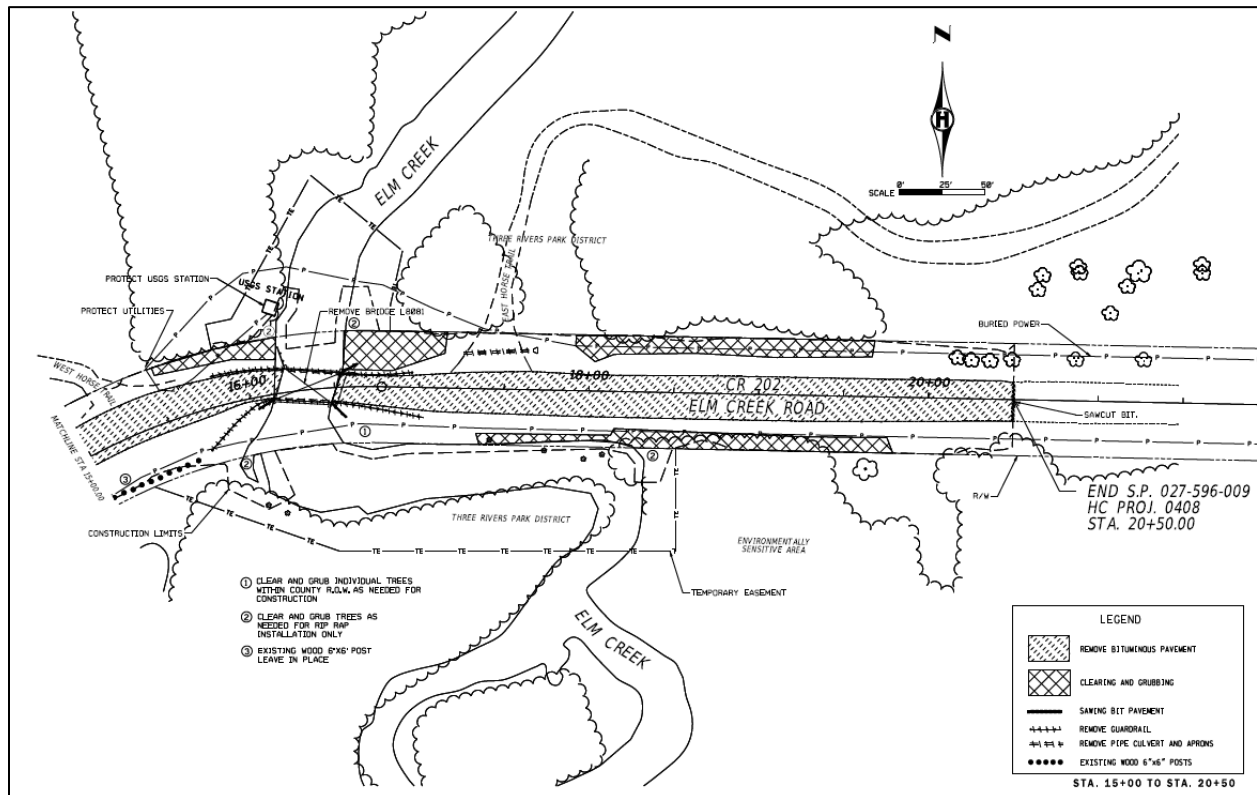


Figure 5.21 Removal plan for bridge L8081. Source: Hennepin County.

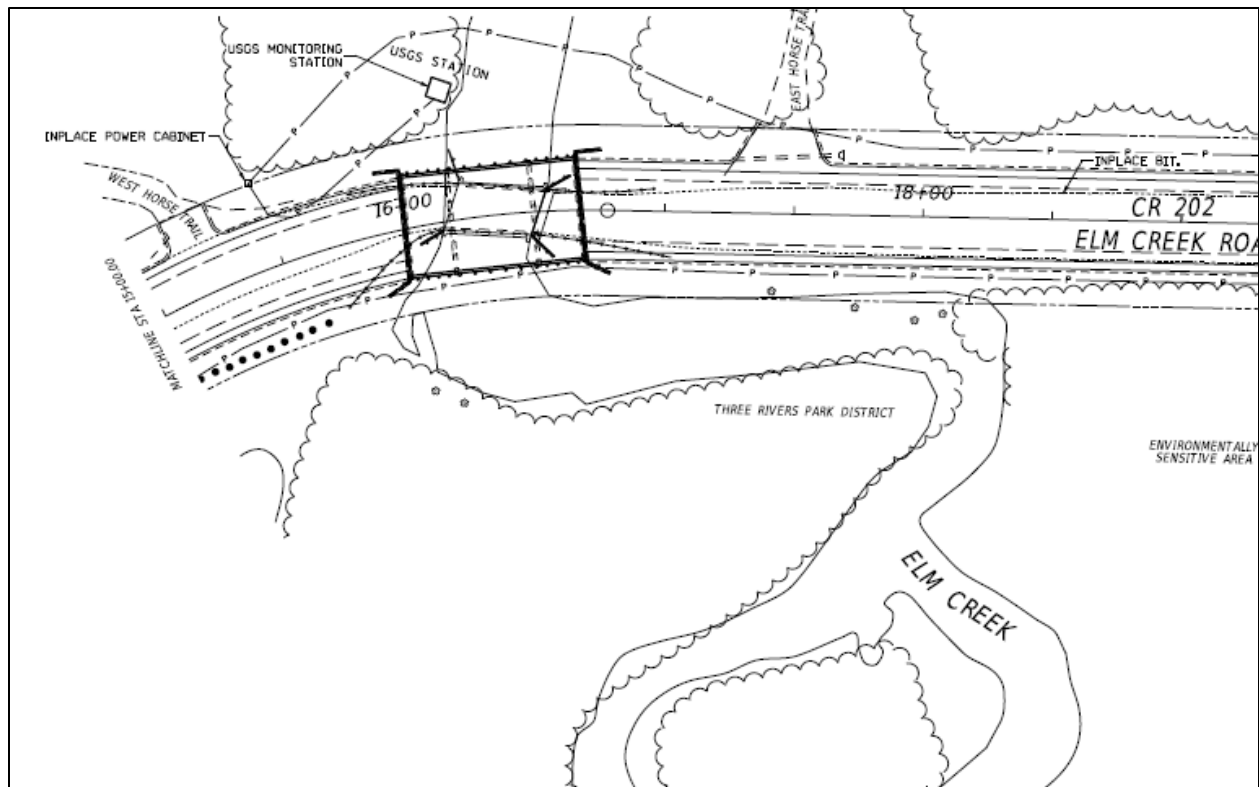


Figure 5.22 Site location showing the existing and new bridges size and orientation. Source: Hennepin County.

5.3.3.2 Cast-in-place (CIP) piling installation, abutment sheet piling, or abutment and steel H-pile caps

Starting in January 2019, the Redstone Construction crew began constructing the new bridge. This included driving CIP piling and installation of steel sheet piling according to the plans in Appendix E. These images show the elevation of the bridge and that it is a super elevated deck with a slope of 5.8% downward to the southern edge of the bridge. This was due to the location of the bridge on a curve. Figures 5.23 to 5.28 show pictures of the abutment sheet piling, CIP pilings, steel H-pile caps for the abutment and piers. Once the substructure work was completed, the project was idled to wait for spring, snow melt and timing of the timber components arrival. While it would have been possible to complete the deck installation in the winter, the decision was made to wait until spring for the timber component installation. This would then shorten the time duration between timber installation and the site earthwork requirements that would need to be completed prior to final bituminous paving.



Figure 5.23 Sheet metal abutment, CIP piling and pier supports after installation.



Figure 5.24 Sheet pile abutment wall and wing wall after installation.



Figure 5.25 Abutment construction with CIP piling, H-beam, and steel sheeting for the abutment and wing wall. Photo credit Hennepin County.



Figure 5.26 CIP piling that has been driven and filled. Photo credit Hennepin County.



Figure 5.27 Substructure showing completed abutments, piers and pollution prevention flotation prior to timber deck installation. Piles are of different heights to meet required roadway super elevation. Photo credit Hennepin County.



Figure 5.28 Completed west abutment showing sheet pile, end wing wall and steel channel cap. Photo credit Hennepin County.

5.3.3.3 Prefabricated dowel-laminated timber deck materials

Following acceptance of the bid, Wheeler Consolidated developed shop drawings for the project as detailed in Appendix E. Upon acceptance of the shop drawings by Hennepin County design engineer and Redstone Construction, the dowel-laminated deck panels, railings and posts were fabricated using preservative treated Douglas fir lumber per design in Whitewood, South Dakota. Holes and slots were predrilled as appropriate based on the shop drawings. Following fabrication, the timber materials and hardware were transported to the bridge location and off-loaded. Care was used to ensure the materials were stored off the ground and a plastic tarp was used to cover the material prior to construction to minimize wetting from any rain events.

A construction crane was used to move the timber panels into location. Span one was installed using panels A18, B18, C18 and D18. Panel A was the first panel installed into its final location on the abutment caps. 13/16 in diameter (\varnothing) holes were drilled through the panel and caps, treated with copper naphthenate, and 3/4 in \varnothing dome head bolts installed and fastened per specification. Panel C was then installed so that the upper splice of the ship lap joint was placed over the lower splice block. The panels were then drawn tight together using a lever hoist. Using the shop drilled holes in the upper splice block as a guide, holes were then drilled into the lower splice block on panel A. 5/8 in \varnothing dome head spikes were driven through the holes. 13/16 in diameter holes were then drilled through the panel and into the abutment cap per plan and fastened with 3/4 in \varnothing dome head bolts. The previous steps were then repeated for the remaining C, D, and B panels. For span 2, panels A32, B32, C32, and D32 were used to follow the same process as identified above. Panels were fastened together over pier using a similar approach; however, a timber panel filler was placed on top of the steel abutment and pier cap for span 1 and span 3. To ensure straightness during construction, all A panels were installed along the full length of the bridge, and then the remaining panels were installed across the width of the bridge. Figures 5.29 to 5.37 show the installation of the panels.

Following installation of all panels, a steel plate was attached over the abutment and timber deck. This detail is intended to minimize any potential gravel or deterioration at the joint between the abutment and the timber deck. An ice and water barrier was specified to be installed over the plate but it was installed under the plate instead. Figures 5.38 and 5.39 show the plate installation and installed water shield over the plate prior to paving.



Figure 5.29 Panel C18 being installed using a crane on span 1. Steel plates are recessed into the deck panel outer lamination approximately 3-ft for the crash-tested bridge railing and curb system. Photo credit Hennepin County.

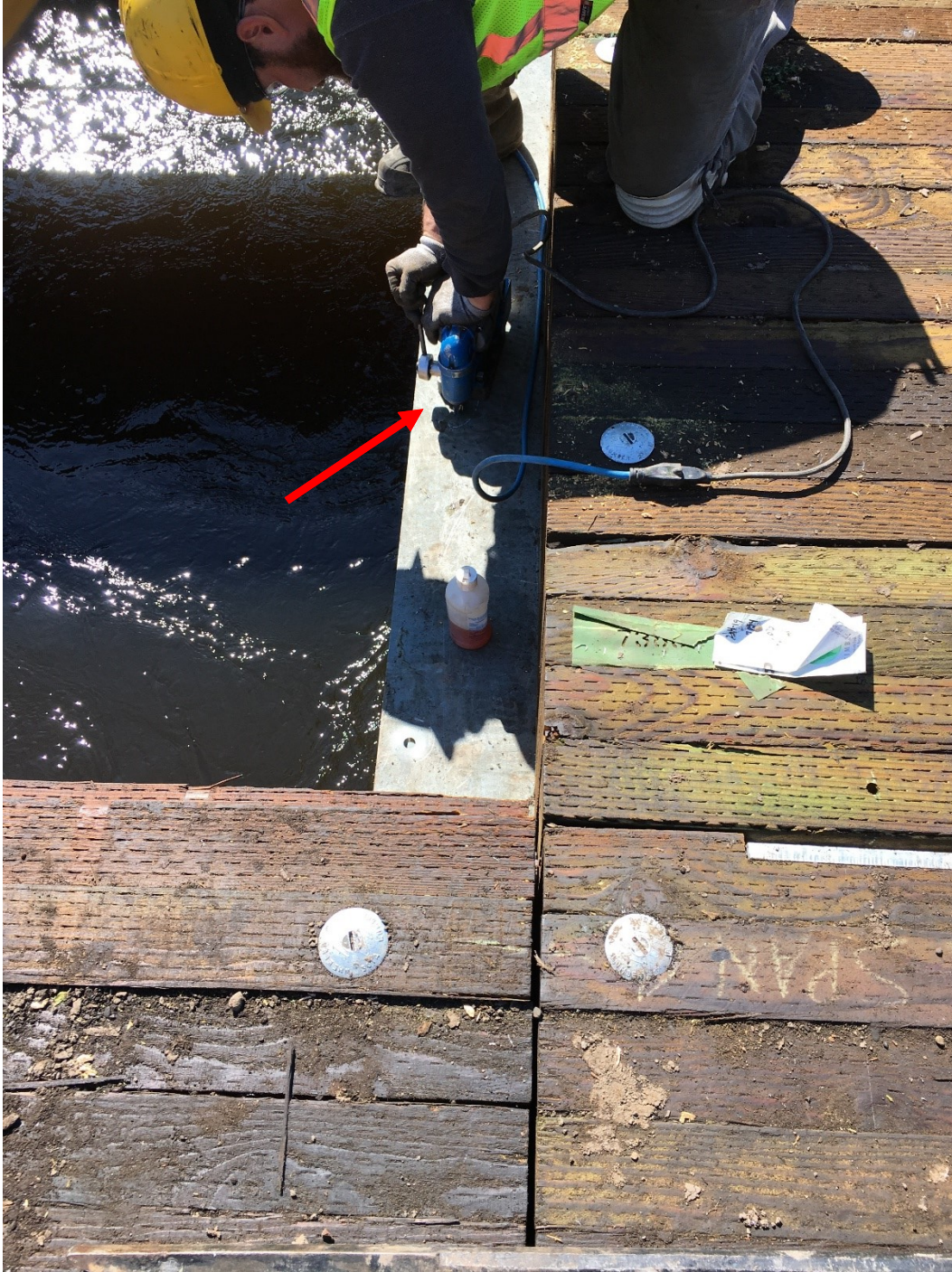


Figure 5.30 Installed panels showing dome head bolts and operator predrilling pier cap prior to installation.
Photo credit Hennepin County.



Figure 5.31 Dome head drive spikes being installed into the panel splice joint. Note the embedded steel plates at this location are installed to help anchor the crash-tested bridge railing and curb system. Photo credit Hennepin County.



Figure 5.32 Installed panel for span 1 with sleeper blocking (identified with red arrow) at pier support to align top of timber decks. Photo credit Hennepin County.



Figure 5.33 Panel installation in progress for spans 1, 2, and 3. Photo credit Hennepin County.



Figure 5.34 Span 3 showing designed gap (identified with red arrow) between panel end and abutment wall. Photo credit Hennepin County.



Figure 5.35 Span 2 panels installed indicating excess width due to misalignment on downstream deck edge that required slight modification. Photo credit Hennepin County.



Figure 5.36 Panel installation and lever hoist used to tighten splice edge joints. Photo credit Hennepin County.



Figure 5.37 Extreme high stream level during deck installation. Design details ensured strong connections between the CIP, pier caps, and timber panels. Photo credit Hennepin County.



Figure 5.38 Steel plate installed over the end of the abutment cap and the end of the timber panels covering the end gap (Figure 5.32). Photo credit Hennepin County.



Figure 5.39 Steel plate at bridge transition after backfill and railings. Photo credit Hennepin County.

5.3.3.4 Crash-Tested Rail, Flashing Materials

Due to the site location on a curve, a Test Level (TL4) (Ritter et al., 1993) crash-tested railing and curb system was installed instead of a TL2 system to enhance safety. Prior to completion of the deck panel installation, the crews initiated construction of the bridge north edge railing system. Details for the railing construction are shown in the construction plan located in Appendix E. To improve long-term durability of the timber materials, a flashing system was designed and fabricated. As initially designed, the intent was to provide protection on the lower edge of the bridge deck that was 5.8% lower than the upper edge. The intent was to flash both the scupper face and the scupper opening as a protection against water. A basic flashing system was designed, but to simplify fabrication and installation, the design engineer specified a plan where a minimum 26-gauge galvanized steel flashing would be installed under the entire length of the bridge on top of the deck and below the scupper and extend a minimum of 3 inches beyond the edge of the bridge deck. Additionally, the scupper opening was flashed to protect the vertical edges of the opening from water. Figures 5.40 to 5.52 show the installation of the railing and installed flashing.



Figure 5.40 North edge of railing being installed prior to deck completion. Photo credit Hennepin County.



Figure 5.41 Prefabrication of the timber curb and scupper blocks (laid out on their side) prior to connection to the deck panels along the north deck edge. Photo credit Hennepin County.



Figure 5.42 Predrilling split ring connectors for scupper to deck connection. Photo credit Hennepin County.



Figure 5.43 Predrilling and inserting split ring connectors at the interface of the timber deck and between the scupper blocks. Photo credit Hennepin County.



Figure 5.44 Curb and scupper aligned prior to connection to deck panels. Photo credit Hennepin County.



Figure 5.45 Curbs, scupper blocks, and rail posts installed along the north edge of the bridge. Embedded steel plates are to reinforce the bridge railing against vehicle impact forces. Photo credit Hennepin County.



Figure 5.46 Rail posts, spacers and railing installed on north edge of bridge. Photo credit Hennepin County.



Figure 5.47 Finalizing crash-tested bridge railing and curb system installation on north edge of bridge. Photo credit Hennepin County.

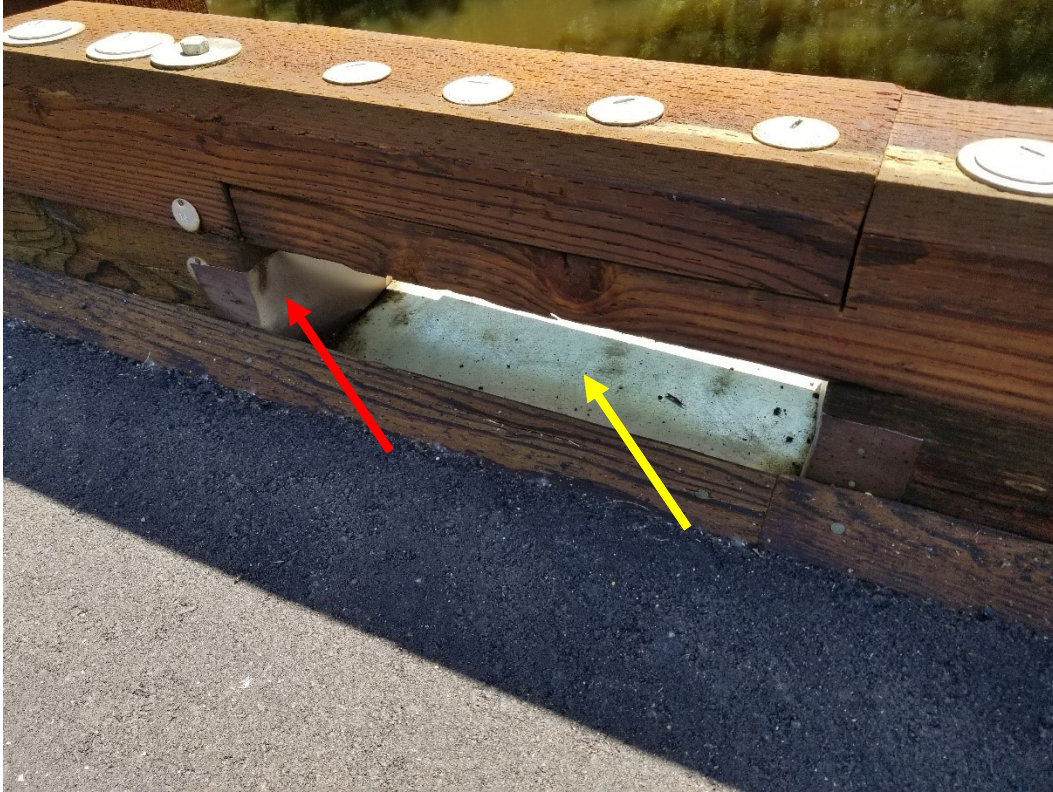


Figure 5.48 Flashing detail includes a full length horizontal flashing (yellow arrow) under the scupper and vertical flashing (red arrow) on the inside of the scupper opening.

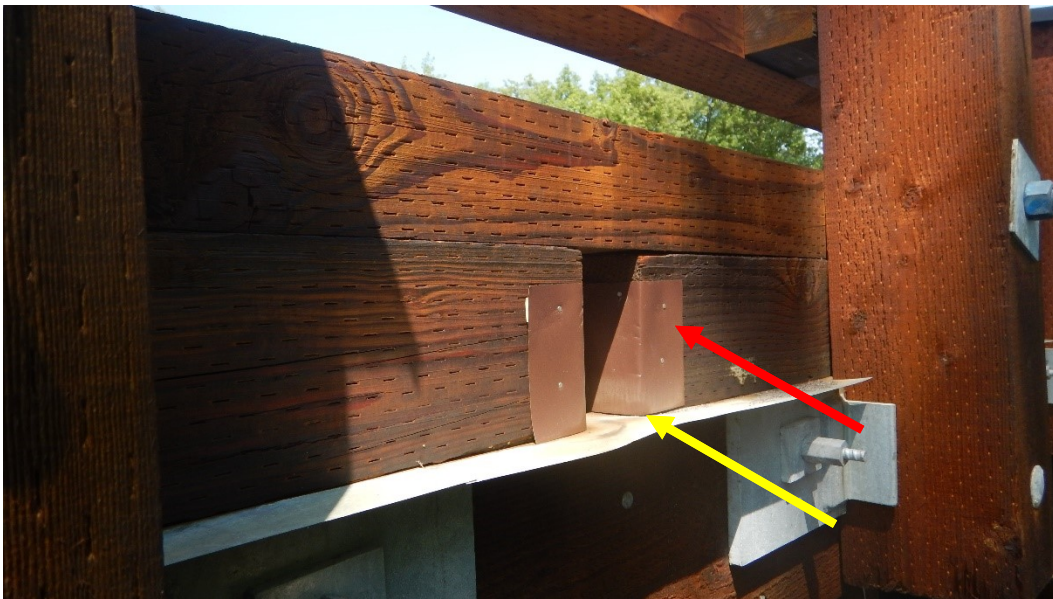


Figure 5.49 Flashing (yellow arrow) extending beyond the south bridge outside edge to divert water from the timber panels. Vertical flashing was also added (red arrow) to protect end grain in the opening.

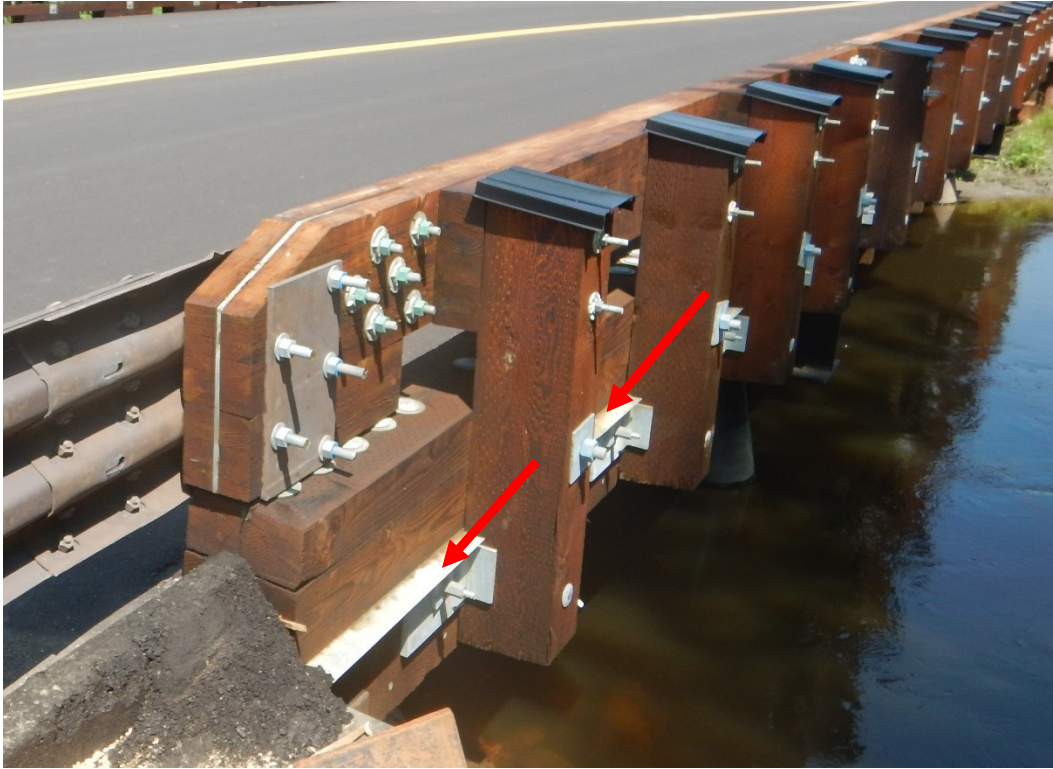


Figure 5.50 South edge of bridge flashing to divert water from bridge deck and away from timber components. Splice connection of the glulam bridge railing with the steel beam approach railing.



Figure 5.51 Plastic rail post flashing to divert water from rail post end grain. Preferred installation is for the screws to attach through the vertical side of the cap.



Figure 5.52 Completed bridge sub- and super-structure installation prior to remaining road site work. Photo credit Hennepin County.

5.3.3.5 Bituminous Overlay, Waterproof Membrane

Following installation of the timber deck, flashing, rail posts and end plates, the roadway approaches were prepared for a bituminous overlay. Based on the bridge approach design in the Hennepin County construction plan fill, grading and compacting was completed. Following that process, bituminous overlay was installed. A tack coat applied to the timber bridge deck prior to paving. Bituminous SP Type 12.5 Wearing Course Mix was used for the project. The bituminous wearing surface was applied in 2 separate layers. Layer one (base course) would be 1 in thick and layer 2 (wearing course) would be 2 in thick for a final bridge bituminous thickness of 3 in. A bituminous membrane overlay was applied between the base course and the wearing course by the construction crew and Hennepin County staff. The membrane was a Mirafi Miratak product. Each roll was 3 ft by 50 ft by 79 mil thickness.

The process steps for installation included:

- The bridge deck was uncovered for 1-2 days prior to paving to ensure a dry surface.
- A tack coat was applied to the timber deck.
- A base layer of bituminous (approximately one inch) was applied to the deck and compacted.

- The bituminous was allowed to cool to 175-200 °F (79-93 °C) prior to adding the ProtectoWrap membrane.
- The ProtectoWrap membrane was rolled out on the top of the base layer and went to within 1 inch of the bituminous edge. The rolls were 3 ft wide by 50 ft long. Overlap was two inches on the edges and 4 inches on the ends. The wrap extended 5 ft beyond the bridge deck onto the approach roadway. Pressure rolling was performed to ensure adhesion, especially at overlapped seams.
- The wear course of bituminous target was 275-300 °F (135-149 °C).
- Final compaction.

Figures 5.53 to 5.57 show the paving process and the installation of the waterproof reinforcing membrane.



Figure 5.53 Roadway approaches and bridge deck prepared for final bituminous paving. Photo credit Hennepin County.



Figure 5.54 First layer (base course) of bituminous overlay being deposited onto timber deck that had a tack coat applied (not shown). Photo credit Hennepin County.



Figure 5.55 Bituminous reinforcing membrane after installation onto the (base course) bituminous layer. Photo credit Hennepin County.



Figure 5.56 Tack coat application prior to first layer of bituminous. Photo credit Hennepin County.



Figure 5.57 Waterproof membrane installed on top of the (base course) bituminous layer in multiple rows. Each row of waterproof membrane was overlapped by 4 inches according to the manufacturers' specifications. Photo credit Hennepin County.

5.3.3.6 Guard Rail, Post Caps

Following paving, the railing was installed according to the construction plan and design details. The guard rails were installed and attached to the bridge rails. Figures 5.58 to 5.61 show the bridge railing installation and connection to roadway guard rails.



Figure 5.58 Completed installation of the crash-tested bridge railing and curb system.



Figure 5.59 Glulam rail splice connection detail with steel approach railing.



Figure 5.60 Approach semi-rigid guardrail system along north side of roadway.



Figure 5.61 View showing TL4 rail system used on this bridge and the installed plastic cap for moisture protection.

Following completion of the bridge, paving and approach guard rails, the road was opened for traffic. Figures 5.62 to 5.66 show the completed roadway and bridge.



Figure 5.62 Completed bridge and paved roadway.



Figure 5.63 Roadway open for traffic facing to the east.



Figure 5.64 Roadway open for traffic facing to the west.



Figure 5.65 Underside view of completed superstructure showing the timber spreader beams (red arrows) at the underside of the timber deck panels.



Figure 5.66 A side view of the completed bridge 27C53 open to traffic. Photo credit Hennepin County.

5.3.3.7 Construction Summary

During the project design, bid, and construction process, significant lessons were learned that could support improvements in future timber bridge construction projects in Minnesota. These include:

1. The bridge is situated in an environmentally sensitive area. This was a challenging site location due to the inherent river flow direction, water levels and weather. The location of the bridge in reference to the stream channel, the frequency of flooding in Elm Creek, and the location of the bridge on a curve presented challenges for the county design engineer. Significant effort was made to meet all appropriate federal, state and local requirements.
 - a. To manage water levels and flow, ditches and culverts were used. Three flood plain culverts were added to the east side of the project. A stormwater pollution prevention plan was required and included temporary erosion control measures, permanent erosion and sediment control measures, final stabilization, and erosion and sediment controls. Additional detail is provided in Appendix E.
 - b. Significant excavation and other work were required to replace the existing one lane bridge with a two lane bridge. Due to the location on a curve, the design required the timber bridge deck to have a super elevated cross slope of 5.8 percent to meet Minnesota Department of Transportation State Aid requirements.

- c. The location of the bridge in a flood plain resulted in the selection of sheet steel piling abutments, CIP piling, steel H-beam abutment and pier caps. Appropriate design connections between the steel piling, caps and timber deck were specified and used.
2. This project was completed by a Redstone Construction, LLC bridge crew. Onsite monitoring and engagement were provided by Hennepin County construction engineer and the engineering technician, facilitating communication and construction monitoring. The construction crew was responsible for all construction activity at the site, including deconstruction, site preparation, gravel delivery, abutment preparation, structural member installation, and all other final roadwork.
3. A major challenge to the overall project was the weather. The project was designed and contracted for winter construction. The removal of the existing bridge was accomplished rapidly, and the installation of the bridge substructure was completed as expected just prior to winter season. Once the substructure was completed, a construction delay was initiated to wait until spring for the superstructure installation. Significant snow and cold was present throughout the winter and a rapid spring melt resulted in extremely high-water levels. Fortunately, the installation of the abutment and pier cap were completed prior to the high water. Following the timber deck installation, significant spring rains occurred, further delaying the construction of the roadway. Paving of the project was not completed until July, resulting in an extended detour. Construction of the timber superstructure was not delayed due to weather.
4. The detailed construction plan and Division Specification Book facilitated the bid process, construction and details for the project. The clarity of the information as presented provided for clear communication between the construction companies and the County, improving the construction process.
5. While a preconstruction meeting was held between the County and the winning contractor, the research project team was unable to attend. For research or demonstration projects with outside partners, it is suggested that future, early stage meetings between the project engineer, construction engineer and the engineering technician be held to clarify any research or demonstration project goals in advance of construction. Further, it is recommended that additional information on the demonstration aspects and project documentation requirements be shared with the full construction crew. It would create additional awareness and familiarity with plan details, construction techniques, and allow for a question/answer session.
6. In this project, changes were made to the plan for flashing the lower slope of the bridge to protect against water. Due to late notice on construction, a modified flashing approach was used. This is an example of where further early stage engagement by the research team would have clarified the intent of the flashing.
7. Discussions with the county representatives, resulted in good feedback for this project. Specifically, they identified the following comments:
 - a. This was the first timber project that each had been involved with, and the result was positive. They affirmed the rapid installation of the timber panels, and the ability to advance the deck and railing installation rapidly. Other benefits noted included minimal on-site fabrication, a quiet construction site, and rapid assembly.
 - b. They noted the positive impact of having some holes pre-drilled to maximize the treating envelope. On-site drilling was required and used to align the deck panels to both the abutment and pier caps and to connect them to each other. All field-drilled holes were field treated with preservatives in accordance with best practices.

- c. The only challenge during installation was that the span two width exceeded the width of spans 1 and 3, requiring on-site modification. It was projected that one or more of the panels may have been slightly wider (but within specification), and that the 32-ft span length of span two made it challenging to close any gaps between panels. The correction was made by field removal of one laminate from the panel adjacent to the bridge edge. This was proposed by the bridge supplier and approved by the county and contractor. The modification to the panel took approximately 2 hours to accomplish and resulted in span 2 bridge width being within the acceptable tolerance range.
 - d. They also reported that the reinforcing membrane that was placed between layers was very simple, much more so than expected. It took less than one-person hour to install.
8. Perhaps the most valuable aspect to the project was time reduction of the construction cycle for the bridge superstructure. For this project, the timber panels were placed and installed in 5 five workdays, and the railing posts, hardware, and rails in two workdays during late winter. While this project was significantly delayed due to other aspects, the actual construction time was minimized using these materials. The timber panels and railing installation was not limited by winter construction.

5.4 COST SUMMARY AND COMPARISON

5.4.1 As-built Design: Dowel-laminated deck panels with metal spikes, transverse spreader beams, and railings.

One of the goals of this project was to track and compare costs for this bridge as compared to options utilizing alternative bridge materials. Table 5.5 provides the bid costs for the timber aspects of this bridge. Due to the use of a bid process, it was not possible to break out other details or to estimate labor costs for the timber installation. Specific design components selected for the project included the use of flashing on the south edge of the bridge deck, a waterproof membrane between layers of bituminous paving on the bridge, and a plastic cap for rail posts. However, these costs were not broken out during the bid process. For the flashing, the Division SB noted that the cost of material and installation should be considered incidental to Item Number 2403.618, laminated deck panels. For the waterproof membrane, the Division SB noted that the procurement, preparation of timber deck and the installation of the timber wear course, waterproof membrane, tack coat, and flashing were incidental to Item Number 2403.618, laminated deck panels. For the plastic post caps, the material and installation were incidental to the Item Number 2403.603, timber railing.

Table 5.5. Cost breakdown for Hennepin County Bridge 27C53.

Category	Bid Estimate
Superstructure – Timber deck panels ¹	\$357,680
Superstructure – Timber Railing	\$22,168
Superstructure Timber Total	\$379,848

The construction progress was documented and the duration for each installation was:

- Timber deck installation (5 workdays)
- Railing posts, hardware (2 workdays)
- Bituminous overlay (1 workday)

5.4.2 Alternative Design: Continuous Concrete Slab with Concrete Deck

Additional cost comparisons/engineer's estimates were completed by LHB, Inc. This engineer's estimate was based on a three span 21 ft – 28 ft – 21 ft, 14 in deep continuous concrete slab span with single slope concrete barriers on each side of bridge. The substructures are comprised of integral reinforced concrete abutments on steel H-piling with 10 ft long wingwalls and pile bent piers with a reinforced concrete cap on 16 in diameter cast-in-place concrete piling. The general criteria used for determining estimate and unit process was:

- The estimate is built off a slightly longer superstructure (approx. 1 ft each end of bridge) due to wider abutment widths required for reinforced concrete substructure types and to match the hydraulic waterway area per Hennepin County Bridge 27C53.
- Proposed substructures include integral type reinforced concrete abutments on 6 – steel H12x53 piling (110 ft per pile) per abutment and pile bent piers with a reinforced concrete cap on 6 – 16 in diameter steel cast-in-place concrete piles (110 ft per pile) per pier.
- 38 ft – 0 in clear roadway and 41 ft – 0 in bridge slab out-to-out width.
- 14 in thick continuous reinforced concrete slab superstructure.

Figure 5.67 shows the design elevation and transverse section. Table 5.6 is an estimate of quantities and cost.

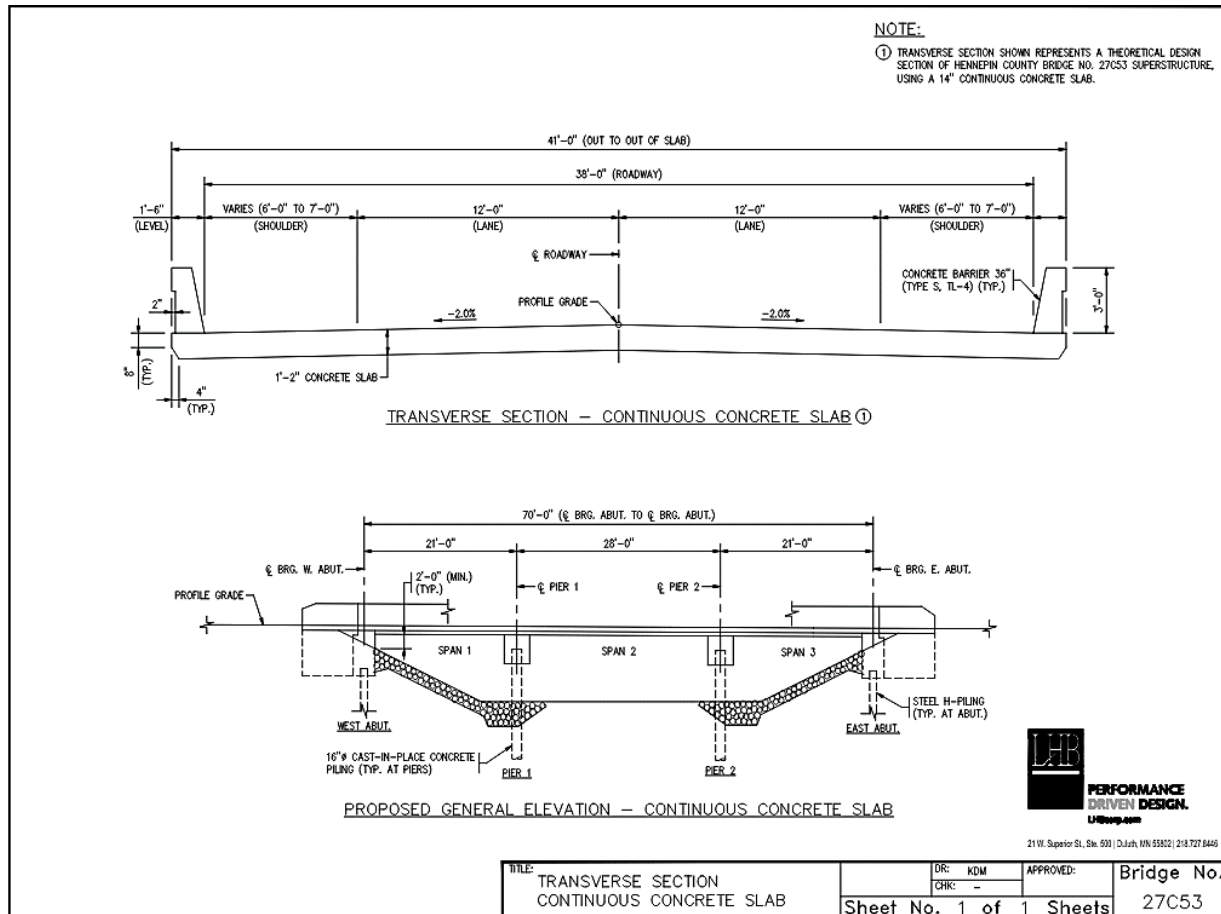


Figure 5.67 General elevation and transverse section of continuous concrete slab superstructure.

Table 5.6 Continuous concrete slab with concrete deck bridge estimated quantities and costs

Item No.	Description	Units	Quantity	Unit Price	Total Price
2021.501	Mobilization	Lump Sum	1	\$60,000.00	\$60,000.00
2401.503	Type S (TL-4) 36" Barrier Concrete (3S52)	Lineal Feet	190	\$140.00	\$26,600.00
2401.507	Structural Concrete (3B52)	Cubic Yard	110	\$1,200.00	\$132,000.00
2401.508	Reinforcement Bars (Epoxy Coated)	Pound	49800	\$1.70	\$84,660.00
2401.601	Structure Excavation	Lump Sum	1	\$25,000.00	\$25,000.00
2401.618	Bridge Slab Concrete (3YHPC-M)	Square Feet	2938	\$52.00	\$152,776.00
2442.501	Remove Existing Bridge	Lump Sum	1	\$30,000.00	\$30,000.00
2452.502	C-I-P Concrete Test Pile 120 ft Long 16"	Each	2	\$13,000.00	\$26,000.00
2452.502	Steel H-Test Pile 120 ft Long 12"	Each	2	\$11,000.00	\$22,000.00
2452.502	Pile Points 16"	Each	12	\$350.00	\$4,200.00
2452.502	Pile Tip Protection 12"	Each	12	\$160.00	\$1,920.00
2452.603	C-I-P Concrete Piling 16"	Lineal Feet	1100	\$55.00	\$60,500.00
2452.603	Steel H-Piling 12"	Lineal Feet	1100	\$38.00	\$41,800.00
2502.501	Drainage System Type (B910)	Lump Sum	1	\$2,500.00	\$2,500.00
2511.504	Geotextile Filter Type 7	Square Yard	1050	\$2.75	\$2,887.50
2511.507	Random Riprap Class IV	Cubic Yard	830	\$80.00	\$66,400.00
Total			\$739,243.50		

Note:

- Items per the 2018 Edition of the Minnesota Department of Transportation Standard Specifications for Construction.
- It was estimated by LHB, Inc. that the substructure and superstructure construction duration would be 10-12 weeks minimum.

5.4.3 Alternative Design: Rectangular Prestressed Concrete Beams with Concrete Deck

Additional cost comparisons/engineer's estimates were completed by LHB, Inc. This engineer's estimate was based on a three span 19 ft – 32 ft – 19 ft, prestressed concrete beam spans with single slope concrete barriers on each side of bridge. The substructures are comprised of integral reinforced concrete abutments on steel H-piling with 10 ft long wingwalls and pile bent piers with a reinforced concrete cap on 16 in diameter cast-in-place concrete piling. The general criteria used for determining estimate and unit process was:

- The estimate is built off a slightly longer superstructure (approx. 1 ft each end of bridge) due to wider abutment widths required for reinforced concrete substructure types and to match the hydraulic waterway area per Hennepin County Bridge 27C53.
- Proposed substructures include integral type reinforced concrete abutments on 6 – steel H12x53 piling (110 ft per pile) per abutment and pile bent piers with a reinforced concrete cap on 6 – 16 in diameter steel cast-in-place concrete piles (110 ft per pile) per pier.
- 38 ft – 0 in clear roadway and 41 ft – 0 in bridge slab out-to-out width
- 6 lines of 14 in rectangular prestressed concrete beams (14RB) at 7 ft – 6 in spacing between beams.

Figure 5.68 shows the design elevation and transverse section. Table 5.7 is an estimate of quantities and cost.

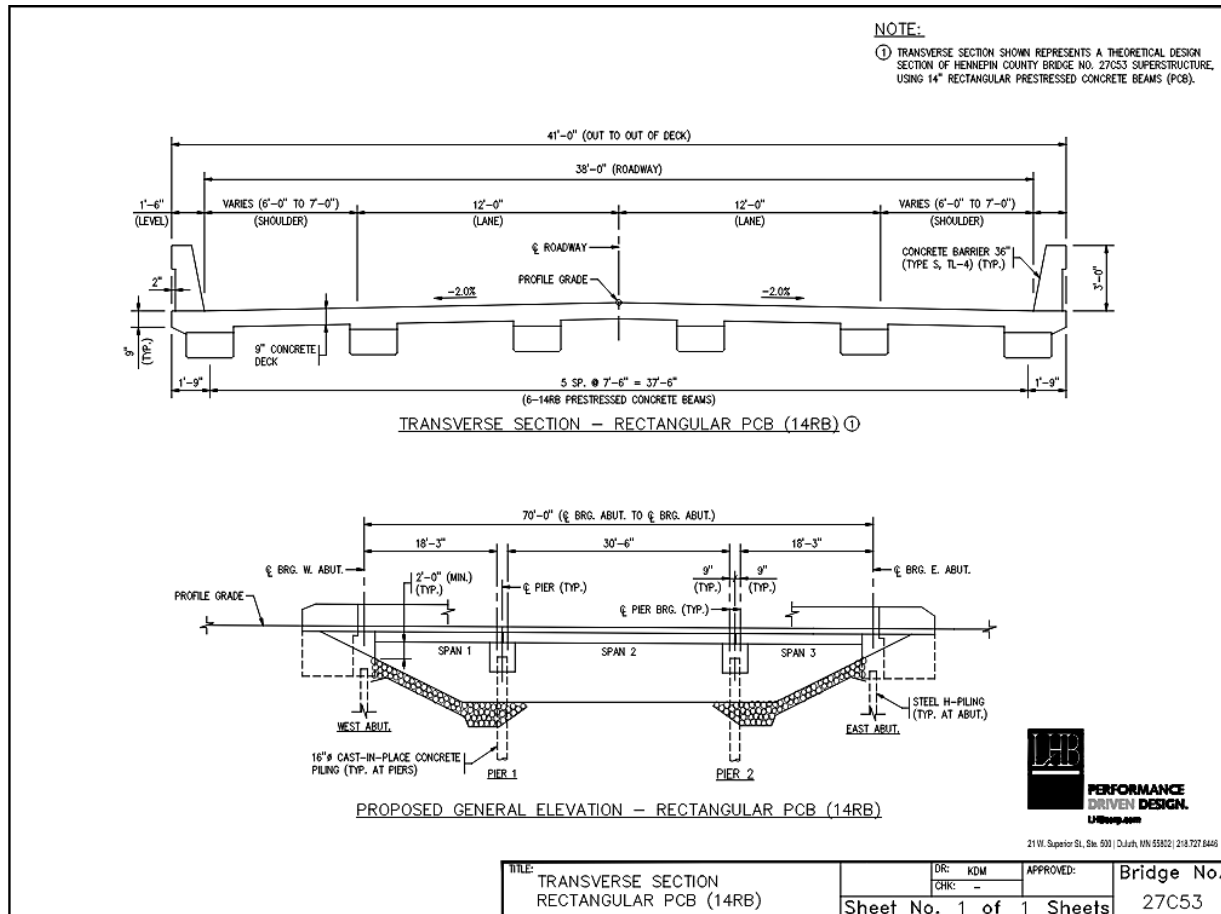


Figure 5.68 General elevation and transverse section of rectangular prestressed concrete beam with a concrete deck superstructure.

Table 5.7 Prestressed concrete beam with concrete deck bridge estimated quantities and costs.

Item No.	Description	Units	Quantity	Unit Price	Total Price
2021.501	Mobilization	Lump Sum	1	\$65,000.00	\$65,000.00
2401.503	Type S (TL-4) 36" Barrier Concrete (3S52)	Lineal Feet	190	\$140.00	\$26,600.00
2401.507	Structural Concrete (3B52)	Cubic Yard	110	\$1,200.00	\$132,000.00
2401.508	Reinforcement Bars (Epoxy Coated)	Pound	31800	\$1.80	\$57,240.00
2401.601	Structure Excavation	Lump Sum	1	\$25,000.00	\$25,000.00
2401.618	Bridge Slab Concrete (3YHPC-M)	Square Feet	2958	\$34.00	\$100,572.00
2402.502	Elastomeric Bearing Pad	Each	36	\$130.00	\$4,680.00
2405.503	Prestressed Concrete Beams 14RB	Lineal Feet	410	\$290.00	\$118,900.00
2442.501	Remove Existing Bridge	Lump Sum	1	\$30,000.00	\$30,000.00
2452.502	C-I-P Concrete Test Pile 120 ft Long 16"	Each	2	\$13,000.00	\$26,000.00
2452.502	Steel H-Test Pile 120 ft Long 12"	Each	2	\$11,000.00	\$22,000.00
2452.502	Pile Points 16"	Each	12	\$350.00	\$4,200.00
2452.502	Pile Tip Protection 12"	Each	12	\$160.00	\$1,920.00
2452.603	C-I-P Concrete Piling 16"	Lineal Feet	1100	\$55.00	\$60,500.00
2452.603	Steel H-Piling 12"	Lineal Feet	1100	\$38.00	\$41,800.00
2502.501	Drainage System Type (B910)	Lump Sum	1	\$2,500.00	\$2,500.00
2511.504	Geotextile Filter Type 7	Square Yard	1050	\$2.75	\$2,887.50
2511.507	Random Riprap Class IV	Cubic Yard	830	\$80.00	\$66,400.00
Total			\$788,199.50		

Note:

- Items per the 2018 Edition of the Minnesota Department of Transportation Standard Specifications for Construction.
- It was estimated by LHB, Inc. that the substructure and superstructure construction duration would be 10-12 weeks minimum.

Life-cycle cost assessments (LCCA) are often completed for transportation construction projects to assess the full service life costs for these projects. For this project, the comparisons for LCCA were limited to the superstructure construction and maintenance costs. Other LCCA estimates may include the cost of inspection and user costs.

For the as-built timber design and the two concrete alternatives, the following information was projected. This includes the initial construction costs, and rehabilitation costs for both the first and second rehabilitation. For this project, an estimated life of the bridge was estimated at 75 years. For this case, deck rehabilitation was estimated at 25 and 50 years for the timber project and 25 and 50 years for the concrete deck project. Estimates of deck repairs was estimated at \$30,000 (2018 dollars) was estimated at 25 years and 50 years for the timber deck and at 50 years for the concrete deck options. Repair and rehabilitation options for the concrete deck could include repair of potholes, shallow overlay, and bridge deck replacement. Further maintenance could include pothole repairs at 10 year time intervals.

5.5 LIFE-CYCLE ASSESSMENT

A preliminary, screening cradle-to-gate life-cycle assessment (LCA) was completed for Hennepin County, Minnesota bridge 27C53, which was constructed on County Road 202 in the Elm Creek Park Reserve. The LCA utilized data from the bill of materials (BOM) and construction drawings, which were provided by Hennepin County (MN), the bridge owner.

The system boundary included material and fuel consumption for timber and steel structural materials fabrication; material and fuel consumption for fabrication of steel hardware, bituminous overlay, and related components; and transport of materials to the construction site. Because this preliminary screening LCA study was cradle-to-gate, use phase activities and disposal/recycling of the timber bridge were excluded. Most of the life-cycle inventory (LCI) data was secondary data from the DATASmart LCI database (LTS, 2019a). This study also used the cut-off approach method for recycling and utilized the LTS 2019 method (LTS, 2019b) to translate the LCI data into environmental impacts, which combines the ReCiPe Endpoint (H) v1.03 method's (Huijbregts et al., 2017) three endpoint categories (Human Health, Ecosystems, Resources) with the Cumulative Energy Demand, Climate Change, and Water Use impact categories.

A screening LCA is helpful to identify where in the product life cycle most environmental impacts occur, as well as which environmental areas are most impacted. This helps in the definition of the goal and scope of future work, if desirable. The screening LCA may also serve as a guide for a full LCA and allow for the refinement of the goal and scope moving forward, while forming the basis of the model for a full LCA. Since a screening-level LCA may use simplified assumptions, the results are only as accurate as those assumptions.

This study was modeled using *SimaPro v9.0* LCA software (Pré, 2016) and follows International Organization for Standardization (ISO) 14044 guidelines (ISO, 2006a) for internal screening LCAs; however, this LCA is not ISO-approved and is not suitable for external statements or documentation.

Screening-level LCAs are used for gathering and analyzing internal information and allow for assumptions and the use of proxy data and do not usually include the exhaustive sensitivity, consistency, or uncertainty analyses required to comply with ISO 14044 guidelines for public disclosure.

5.5.1 Goal and Scope Definition

The first phase of an LCA defines the goal and scope of the study. According to ISO 14044, the goal of the study should clearly specify the intended application, reasons for carrying out the study, the intended audience, and whether the results are intended to be disclosed to the public. The scope of the study describes the most important aspects of the study, including the functional unit, system boundaries, cut-off criterion, allocation, impact assessment method, assumptions, and limitations.

The objective of this study was to determine the potential environmental impacts of Hennepin County, Minnesota bridge 27C53. The results could be used to inform the Minnesota Department of Transportation (MnDOT) and their stakeholders of the environmental profile of the bridge.

5.5.1.1 Function

The function of the bridge is to support automobile, pedestrian, and bicycle traffic over Elm Creek in the Elm Creek Park Reserve.

5.5.1.2 Functional Unit

A functional unit identifies the primary function(s) of a system based on which alternative systems are considered functionally equivalent (ISO, 2006b). This facilitates the determination of reference flows for each system, which in turn facilitates the comparison of two or more systems. Based on the identified function, the following functional unit was used to determine the reference flows: one steel and timber bridge with a width of 40 ft and a length of 68 ft.

5.5.1.3 System Boundaries

System boundaries are established in LCA in order to include the significant life-cycle stages and unit processes, as well as the associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life-cycle stages, and the flows associated with each alternative, are considered. Included in the system boundary of this study are:

- Material and fuel consumption for timber and steel materials fabrication;
- Material and fuel consumption for fabrication of steel hardware and related components;
- Material and fuel consumption for bituminous overlay; and
- Transport of materials to the construction site.

5.5.1.4 Excluded Processes

Because this preliminary screening LCA study is cradle-to-gate, use-phase activities and disposal/recycling of the bridge components are excluded. Materials packaging is also excluded from the study. Typically, in an LCA, some aspects within the set boundaries are excluded due to statistical

insignificance or irrelevancy to the goal and scope. Thus, the following impacts were also excluded from the scope and boundaries for this study:

- Human activities (e.g., employee travel to and from work); and
- Services (e.g., the use of purchased marketing, consultancy services and business travel).

5.5.1.5 Cut-off Criteria

Cut-off criteria are often used in LCA practice for the selection of processes or flows to be included in the system boundary. The processes or flows below these cut-offs or thresholds are excluded from the study. Several criteria are used in LCA practice to decide which inputs are to be considered, including mass, energy and environmental relevance. In the current study, every effort was made to include all the flows associated with the processes studied. During the interpretation phase, we used 1% of environmental load as a cut-off.

5.5.1.6 Allocation and Recycling

While conducting an LCA, if the life cycles of more than one product are connected, allocation of the process inputs should be avoided by using the system boundary expansion approach. If allocation cannot be avoided, an allocation method – based on physical causality (mass or energy content, for example) or any other relationship, such as economic value – should be used (ISO, 2006a). All allocations were completed based on mass.

This study used the cut-off approach method for recycling. According to this approach, the first life of a material bears the environmental burdens of its production (e.g., raw material extraction and processing) and the second life bears the burdens of refurbishment (e.g., collection and refining of scrap). The burdens from waste treatment are taken by the life after which they occur (Frischknecht, 2010). Given that DATASMART LCI data (LTS 2019a) uses the cut-off approach for recycling, it is considered a reasonable default.

5.5.1.7 Impact Assessment Method

Impact assessment methods are used to convert LCI data (environmental emissions and raw material extractions) into a set of environmental impacts. ISO 14044 (ISO, 2006a) does not dictate which impact assessment method to use for a comparative assertion; however, the chosen method needs to be an internationally-accepted method if the results are intended to be used to support a comparative assertion disclosed to the public.

The impact assessment method used for this study was the LTS 2019 method (LTS, 2019b), which combines the ReCiPe Endpoint (H) v1.03 method's (Huijbregts et al., 2017) three endpoint categories (Human Health, Ecosystems, Resources) with the Cumulative Energy Demand (CED) v1.11 (Frischknecht et al., 2007), Climate Change IPCC 2013 GWP 100a v1.03 (IPCC 2013), and Water Use (Huijbregts et al., 2017) impact categories. These six categories have been found to be of interest and readily

understandable to readers of LCA reports. The LTS 2019 impact assessment method (LTS, 2019b) is summarized in Table 5.8.

Table 5.8 LTS 2019 impact assessment method (LTS 2019b).

Impact Category	Method	Unit
Human Health	ReCiPe 2016 Endpoint (H) v1.03	DALY
Ecosystems	ReCiPe 2016 Endpoint (H) v1.03	species*yr
Resources	ReCiPe 2016 Endpoint (H) v1.03	\$
Cumulative Energy Demand	CED v1.11	MJ
Climate Change	IPCC 2013 GWP 100a v1.03	kg CO ₂ eq.
Water Use	ReCiPe 2016 Endpoint (H) v1.03	m ³

ReCiPe is one of the most recent and updated impact assessment methods available to LCA practitioners. The method addresses several environmental concerns at the midpoint level and then aggregates the midpoints into a set of three endpoint categories. Endpoint characterization models the impact on Areas of Protection (i.e., on human health, ecosystems, and resources). In other words, endpoint is a measure of the damage – at the end of the cause-effect chain – caused by a stressor in terms of human life-years lost and the years lived disabled, species disappeared, and resources lost.

The Cumulative Energy Demand (CED) of a product is the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal. The CED method considers both renewable and non-renewable energy and the direct and indirect energy consumption.

The IPCC 2013 method for assessing the Global Warming Potential (i.e., Climate Change) was developed by Intergovernmental Panel on Climate Change (IPCC). It is one of the most widely used methods to estimate climate change potential of global warming gases in LCA studies. The global warming factors have been developed for 20-, 100-, and 500-year time horizons to address the global warming potential of emissions in the short as well as long term. This study uses the climate change factors for the 100-year time horizon.

5.5.1.8 Endpoint Categories

- **Human Health.** In this category, the damage analysis links the six midpoint categories (Climate Change, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter Formation, Ionizing Radiation, and Ozone Depletion) to the Disability Adjusted Life Years (DALYs). The DALY tool is primarily a disability weighting scale of 0 – 1, where 0 represents perfect health and 1 represents death.
- **Ecosystems.** The damage to ecosystems is measured by calculating the species that disappear in each time period and area. The unit of damage assessment is species lost in one year (species*yr). The midpoint impact potentials that apply to ecosystem quality are: Climate Change, Terrestrial

Acidification, Freshwater Eutrophication, Ecotoxicity, Agricultural Land Occupation, Urban Land Occupation, and Natural Land Transformation.

- Resources. The two midpoint categories contributing to the resources category are Fossil Depletion and Metal Depletion. The quantification of the damage is based on the marginal increase of cost due to the extraction of resources, measured as dollars per kilogram (\$/kg).

5.5.1.9 Midpoint Categories

- Cumulative Energy Demand. This category includes non-renewable (fossil and nuclear) and renewable (biomass, water, solar, wind, and geothermal) energy sources. Characterization factors are based on the upper (or higher) heating value. Characterization factors are expressed as equivalent megajoules (MJ).
- Climate Change. There are several gaseous emissions that cause global warming, including carbon dioxide, methane, nitrous oxides, and fluorinated gases. This category combines the effect of the periods of time that the various greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The global warming potential is measured as kg equivalents of radiation CO₂ (i.e., the relative global warming potential of a gas as compared to CO₂). The IPCC model with a 100-year time horizon is used for characterization. The uptake of CO₂ from the air (i.e., sequestration of CO₂ by plants) and the subsequent emission of biogenic CO₂ (from the burning of biomass) is not included.
- Water Use. Water use is based on water consumption, which is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea (Falkenmark et al., 2004). Water that has been consumed, therefore, is no longer available in the watershed of origin for humans nor for ecosystems.

5.5.1.10 Limitations of the Study

This is a cradle-to-gate screening LCA using mainly secondary data. To make external claims per ISO 14044 (ISO, 2006a), this study would need to be expanded to include:

- Cradle-to-grave system boundary (to include distribution transport, use, and end-of-life phases);
- Primary data for key processes;
- Additional sensitivity analyses;
- Data quality requirements and indicators; and
- Critical review.

5.5.1.11 Limitations of LCA Methodology

LCA's ability to consider the entire life cycle of a product makes it an attractive tool for the assessment of potential environmental impacts. Nevertheless, like other environmental management analysis tools, LCA has several limitations.

With current availability of data, it is nearly impossible to follow the entire supply chain associated with the product life in a company- or manufacturer-specific way. Instead, almost all processes within the supply chains are modeled using average industry data with varying amounts of specificity (e.g., data on a more-or-less specific technology or region). This makes it difficult to accurately determine how well the unit process data represents the actual factors in the products' life cycle. It also makes it difficult to know in which region the processes are found.

Furthermore, LCA is based on a linear extrapolation of emissions with the assumption that all the emissions contribute to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while the linear extrapolation is a reasonable approach for more global and regional impact categories such as Global Warming Potential (GWP) and Acidification, it may not accurately represent the actual on-the-ground human- and ecotoxicity-related impacts.

Additionally, even if the study has been critically reviewed, it should be noted that, as for any LCA, the impact assessment results generated for this study are relative expressions and do not predict impacts on category midpoints, exceeding thresholds, or risks. It should also be noted that, even though LCA covers a wide range of environmental impact categories, some types of environmental impacts (e.g., noise, social, and economic impacts) are typically not included in LCA.

5.5.2 Life-Cycle Inventory

The second phase of an LCA is to collect life-cycle inventory (LCI) data. LCI data contains the details of the resources flowing into a process and the emissions flowing from a process to air, soil, and water.

5.5.2.1 LCI Data Collection

As previously noted, secondary inventory data was used in this study for most processes, with most it readily available in the DATASMART LCI database (LTS, 2019a).

TREATED SOLID TIMBER PRODUCTION

The spreader beams, spreader beam splices, rail posts, post blocks, transition blocks, curbs, scuppers, and edge strips were all manufactured from copper naphthenate (CuNap)-treated solid timber. These materials were assumed to be manufactured from kiln-dried softwood. Selected life-cycle inventory data for the CuNap-treated solid timber are listed in Table 5.9.

Table 5.9 Selected life-cycle inventory data for 1,000 ft³ of CuNap-treated solid timber.

Description	LCI Data Source	Quantity	Unit
Water	Water, unspecified natural origin, US	1.3×10^0	gal
LPG	Liquefied petroleum gas, combusted in industrial boiler NREL/US U	7.9×10^{-1}	gal
Diesel	Diesel, combusted in industrial equipment NREL/US U	1.9×10^1	gal
Gasoline	Gasoline, combusted in equipment NREL/US U	1.6×10^0	gal
Waste wood	Wood waste, unspecified, combusted in industrial boiler NREL/US U	5.5×10^3	lb.
Transport	Transport, lorry 3.5-16t, fleet average/US- US-EI U	7.3×10^3	t-mi
Copper naphthenate	LCA model	6.0×10^2	lb.
Solid timber	Sawn Lumber, softwood, planed, kiln dried, at planer mill, INW/m ³ /RNA	1.0×10^3	ft ³
Natural gas	Natural gas, combusted in industrial boiler NREL/US U	2.0×10^3	ft ³
Electricity	Electricity, medium voltage, at grid, 2015/US US-EI U	9.2×10^2	kWh

TREATED GLULAM RAILING PRODUCTION

The glulam railings were manufactured from CuNap-treated glued timber (glulam) designed for outdoor use. The glulam was assumed to be manufactured from softwood at 20% moisture content and bonded with a melamine formaldehyde resin. Selected life-cycle inventory data for the CuNap-treated glulam are listed in Table 5.10.

Table 5.10 Selected life-cycle inventory data for 1,000 ft³ of CuNap-treated glulam.

Description	LCI Data Source	Quantity	Unit
Water	Water, unspecified natural origin, US	1.3×10^0	gal
LPG	Liquefied petroleum gas, combusted in industrial boiler NREL/US U	7.9×10^{-1}	gal
Diesel	Diesel, combusted in industrial equipment NREL/US U	1.9×10^1	gal
Gasoline	Gasoline, combusted in equipment NREL/US U	1.6×10^0	gal
Waste wood	Wood waste, unspecified, combusted in industrial boiler NREL/US U	5.5×10^3	lb.
Transport	Transport, lorry 3.5-16t, fleet average/US- US-EI U	7.3×10^3	ton-mi
Copper naphthenate	LCA model	6.0×10^2	lb.
Glulam	Glued laminated timber, outdoor use, at plant/US- US-EI U	1.0×10^3	ft ³
Natural gas	Natural gas, combusted in industrial boiler NREL/US U	2.0×10^3	ft ³
Electricity	Electricity, medium voltage, at grid, 2015/US US-EI U	9.2×10^2	kWh

CUNAP-TREATMENT PROCESS

LCI data was not available for CuNap in the DATASmart LCI database, so a new process was created based on previous literature (Bolin and Smith, 2011; Tsang et al., 2014). It was assumed that the yield of treated wood was 100%. The life-cycle inventory data for the CuNap preservative are listed in Table 5.9.

Table 5.11 Life-cycle inventory data for 293.85 g of copper naphthenate.

Description	LCI Data Source	Quantity	Unit
Oxygen	Oxygen, in air	63.96	g
Copper	Copper oxide, at plant/US- US-EI U	79.545	g
Methyl cyclopentane	Methyl cyclopentane, from naphtha, at plant/US- US-EI U	168.324	g

NAIL-LAMINATED DECK PANEL PRODUCTION

The nail-laminated deck panels (nail-lam) were manufactured from CuNap-treated solid timber, as described in Table 5.2, and 3/8-in diameter galvanized steel nails. (The length of the nails was either 11 or 15 in, depending on the size of the finished panel.)

STRUCTURAL STEEL

The rail splice plates, guardrail transition plates, post plate assemblies, and internal steel plates were assumed to be manufactured from hot-rolled sheet steel with a density of 490 lb./ft³, which was then galvanized.

WATERPROOF MEMBRANE

The waterproof reinforcing membrane for the bridge deck was assumed to be manufactured from butadiene styrene sheeting with a weight of 0.26 lb./ft². Selected life-cycle inventory data for the waterproof membrane are listed in Table 5.12.

Table 5.12 Selected life-cycle inventory data for 1 kg of waterproof membrane.

Description	LCI Data Source	Quantity	Unit
Sand	Sand (in ground)	5.3×10^{-1}	kg
Shale	Shale (in ground)	6.8×10^{-1}	kg
Pitch	Proxy Pitch 100#/CN	1.8×10^0	kg
Pitch	Proxy Pitch 10#/CN	2.1×10^{-1}	kg
Styrene butadiene styrene	Proxy_SBS/CN	2.5×10^{-1}	kg
Polyester	Proxy_Polyester materials/CN	7.9×10^{-1}	kg
Insulation	Proxy_Glass wool heat insulation/CN	2.6×10^{-1}	kg
Polyethylene	Proxy_PE film/CN	1.1×10^0	g
Transport	Transport, train, average/CN U	1.1×10^{-1}	t-km
Transport	Transport, lorry, 2-5t, suburb, average/CN S	1.0×10^{-1}	t-km
Coal	Hard coal supply mix/CN US-EI U	3.9×10^{-1}	kg
Electricity	Electricity mix/CN US-EI U	9.5×10^{-2}	kWh

BITUMINOUS OVERLAY

The bituminous overlay was assumed to be asphalt with a density of 145 lb./ft³. 646 ft³ of asphalt was required to cover the bridge (with a 3-in thickness); however, asphalt for the bridge approaches was excluded from the study. Selected life-cycle inventory data for the bituminous overlay are listed in Table 5.13.

Table 5.13 Selected life-cycle inventory data for 1 kg of bituminous overlay (mastic asphalt).

Description	LCI Data Source	Quantity	Unit
Bitumen	Bitumen, at refinery/US* US-EI U	8.0×10^{-2}	kg
Diesel	Diesel, burned in building machine/GLO US-EI U	2.2×10^{-2}	MJ
Electricity	Electricity, medium voltage, at grid/CH* US-EI U	2.8×10^{-2}	kWh
Heat	Heat, light fuel oil, at industrial furnace 1MW/US* US-EI U	1.5×10^0	MJ
Limestone	Limestone, milled, packed, at plant/US* US-EI U	2.6×10^{-1}	kg
Sand	Sand, at mine/US* US-EI U	6.6×10^{-1}	kg
Transport	Transport, freight, rail/US- US-EI U	1.6×10^{-2}	t-km
Transport	Transport, lorry 20-28t, fleet average/US* US-EI U	5.4×10^{-2}	t-km

STEEL HARDWARE

All bolts, nuts, washers, and connectors were manufactured from galvanized low-alloyed steel.

ELECTRICITY MIXES

The electricity usage was modeled using the 2015 average US electricity grid process from the DATASMART LCI database (LTS, 2019a). (These values are taken from 2015 US Energy Information Administration (EIA) data.) The electricity grid mix is a mix of domestic production from various sources, and the average grid mix for the electricity datasets used in this study is shown in Table 5.14.

Table 5.14 Average electricity grid mix for the US.

Electricity source	2015
Hard coal	33.17%
Oil	0.69%
Natural gas	32.70% (47% shale)
Industrial gas	0.16%
Petroleum coke	0.16%
Nuclear	19.55%
Hydro	6.11%
Cogen	0.103%
Geothermal	0.39%
Solar PV	0.61%
Wind	4.68%
Canadian imports	0.31%
Mexican imports	0.03%

5.5.2.2 Data Quality

The quality of the data used in this preliminary LCA is reasonably accurate and representative of the processes modeled. However, Data Quality Requirements and Indicators (DQI) have not been assigned to this study. (This includes evaluation of data reliability, completeness, geographical correlations, further technological correlation, and sample size using the Pedigree Matrix (Weidema and Wesnaes, 1996; Frischknecht et al., 2004).

5.5.3 Results of Life-Cycle Impact Assessment

The following sections summarize the key characterized results of the LCA including contribution analyses.

5.5.3.1 Bridge Life Cycle

Table 5.15 presents the life-cycle impacts for the completed 27C53 bridge.

Table 5.15 Life-cycle impacts of the 27C53 bridge using the LTS 2019 method (LTS, 2019b).

Damage Category	Unit	27C53 Bridge
Human Health	DALY	0.171
Ecosystems	species*yr	2.36×10^{-4}
Resources	\$	5.95×10^3
Cumulative Energy Demand	MJ	8.11×10^5
Climate Change	kg CO ₂ eq.	4.11×10^4
Water Use	m ³	579

5.5.3.2 Contribution Analysis

Contribution analyses identify the environmental hot-spots within the bridge system, which are the processes that contribute disproportionately to the overall life-cycle impacts of the system. The identification of hot-spots provides a deeper understanding of what is driving the environmental performance of the completed bridge and allows for the identification of opportunities for process improvement. The contribution analysis for the completed bridge is shown in Figure 5.69.

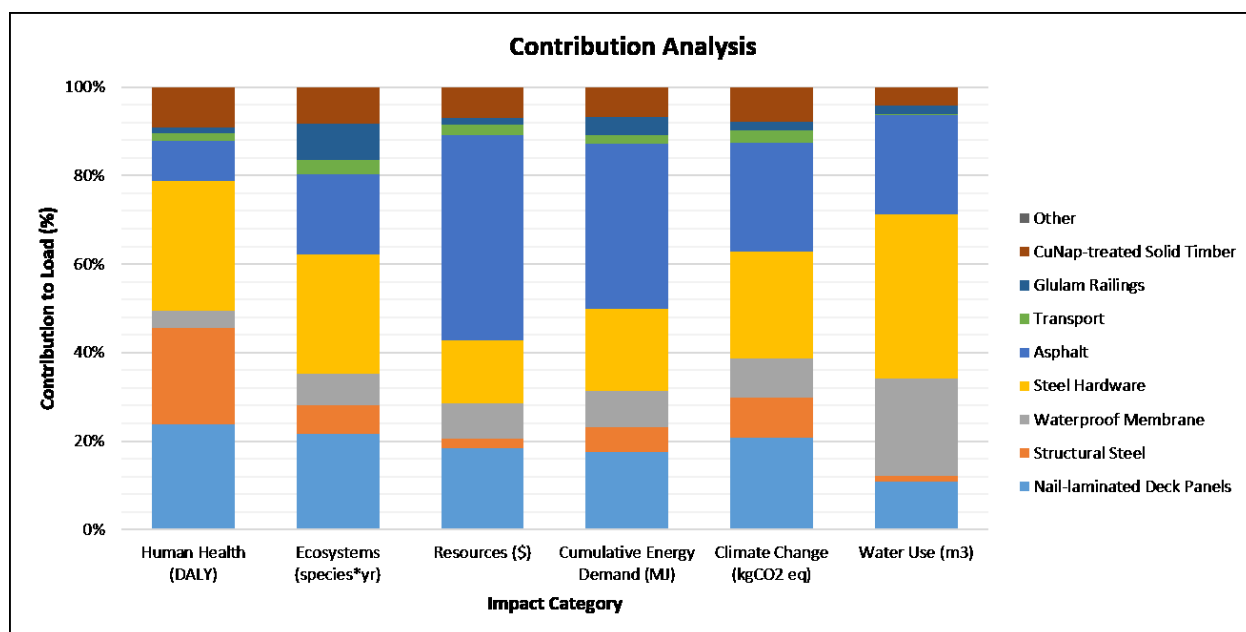


Figure 5.69 Contribution analysis for the completed 27C53 bridge using the LTS 2019 method (LTS, 2019b).

As shown, the bituminous (asphalt) overlay accounted for the largest portion of the impacts in most impact categories, contributing 18%, 46%, 37%, 25%, and 22% of the impacts in the Ecosystems, Resources, Cumulative Energy Demand, Climate Change, and Water Use impact categories, respectively. Production and use of the steel hardware also contributed a large portion of the impacts in each impact category, accounting for 14% to 37% of total impacts. The nail-laminated deck panels accounted for 24%, 22%, 18%, 18%, and 21% of the impacts in the Human Health, Ecosystems, Resources, Cumulative Energy Demand, and Climate Change impact categories, respectively. The structural steel accounted for less than 10% of the total impact in each impact category, except for Human Health, where it accounted for 22% of impacts. Likewise, the waterproof membrane accounted for less than 10% of the total impact in each impact category, except for Water Use, where it contributed 22% of impacts. The glulam railings CuNap-treated solid timber components, and transport contributed less than 10% to each impact category.

5.5.4 Life-Cycle Conclusions

In addition to strictly financial costs of the Hennepin County bridge project, one objective of the LCA study was to understand the environmental impacts of the 27C53 bridge on a cradle-to-gate basis. Environmental assessments are becoming more common in building construction, and it is projected that they will also increase in importance for the bridge construction sector. The bituminous (asphalt) overlay generally accounted for the largest impact in most impact categories, ranging from 9% to 46%, while the nail-laminated deck panels contributed 18% to 24% of the impacts in five of the six impact categories. The steel hardware, structural steel, and CuNap-treated solid timber components contributed an average of 25%, 8%, and 5% of the impacts in each impact category, respectively. While the scope of project was not to compare the environmental performance of the timber bridge to an

equivalent concrete bridge, this does provide key information for future research activity and offers a guideline for future environmental assessments.

CHAPTER 6: CONCLUSIONS

The focus of this project was to create cost-competitive timber bridge design and construction information to support new construction and improve the long-term performance of timber bridges. This information, gained through project activities informed by literature reviews, surveys of county engineers, and demonstration construction projects, was targeted to support an increase in the construction of timber-based bridges in Minnesota. Key conclusions from this report included:

- The main advantage of the timber bridge option is its accelerated construction time for bridge superstructure installation. It is clear from previous case studies, interviews with engineers, contractors, and suppliers, and demonstration projects that timber bridge superstructures can typically be installed within a 1- to 2-week timeframe, as compared to significantly longer timeframes for non-timber superstructures. Prefabrication and assembly of timber bridge components into girder systems or partial-width deck panels is accomplished at the manufacturing facility, which helps minimize traffic disruptions and significantly reduce on-site construction costs. Another significant advantage is the ability to construct timber bridge superstructures during the winter season without detrimental effects to material integrity.
- Timber-based bridge construction projects are infrequent in Minnesota, significantly trailing bridges built from steel and concrete components and/or precast concrete culverts. The majority of the timber-based bridge construction projects were in just a handful of Minnesota counties. It is clear from county surveys that there is significantly less familiarity with timber bridges than with other materials, and a general perception that timber bridges are not a long-lasting or cost-competitive bridge option. In contrast, a recent nationwide timber inspection study convened by a team of government and university researchers indicated that timber bridges can achieve a 70-year service life. The bridge service life could extend even further when key drainage and flashing details are coupled with effective nondestructive inspection and routine maintenance practices.
- Minnesota has two timber bridge component suppliers, Wheeler Lumber, LLC and Bell Structural Systems. These companies have significant experience in working with local bridge owners and engineers to support the design and construction of timber bridges that are cost-effective and long-lasting. Further, there are several bridge companies outside of Minnesota with specialized experience in the design, specification, and construction of timber-based bridge construction projects.
- Several Minnesota construction firms have experience in constructing timber bridges, but this experience is limited mainly to the spike-laminated timber deck “slab-type” bridge system. A few counties maintain their own “in-house” construction crews that construct new timber bridges each year, which may result in a cost savings. To help construction firms learn more about the key aspects of timber bridge construction, additional resources are available. The St. Louis County and the Hennepin County bridge construction case studies documented in this report should provide key details and perspectives on preferred construction methods. In addition, several construction videos on timber bridge superstructure assembly methods are

available through the National Center for Wood Transportation Structures accessible at www.woodcenter.org.

- Engineers and local bridge owners surveyed in this study reported an awareness of life-cycle cost assessment (LCCA) methods, a tool used to assess various construction or repair decisions and identify the most cost-effective approach. Several engineers and local bridge owners reported they utilize a variation of the LCCA method to manage their bridge projects. At the same time, this group also reported a general lack of awareness of life-cycle assessment (LCA) methodology. LCA looks beyond economic cost factors and evaluates the environmental impacts of a product or system on a cradle-to-grave basis in a more holistic approach. It was also evident from survey responses that there aren't any design considerations currently being used in Minnesota for improving the environmental footprint (i.e., carbon emissions, embodied energy and carbon storage) of bridge construction projects.
- Life-cycle assessments (LCA) were completed for each of the two demonstration projects. This LCA analysis work was limited to the actual design and materials used for the two demonstration projects detailed in this report. Of significant impact in these LCA studies was the use of a bituminous asphalt wearing surface in conjunction with a waterproof geotextile membrane. These results will establish key baseline data on timber bridge LCA analyses, and future investigations can extend this work by developing comparative LCAs of the design and materials for competing bridge materials. As more attention is focused on the sustainability of all constructed facilities in the future, LCA assessments will likely be a higher consideration for local bridge owners and design engineers.
- Additional measures are under consideration for improving the cost-effectiveness of Minnesota timber bridges. These measures include: a more streamlined MnDOT approval process for waivers with regard to preservative selection; contracting options that include inclusion of timber design information into the contract bidding process to foster more cost-competitive awards; further investigation into contractor supplied bridge superstructure designs to improve the cost-effectiveness of timber bridges for local roads in Minnesota.
- Several aspects of the current AASHTO-LRFD bridge design specifications can be advantageous to timber bridges and can result in significant cost savings during material fabrication. Since most timber bridges are located on secondary roads with low traffic volume, a favorable multiple-presence factor can be utilized when the average daily traffic over the bridge is projected to be less than 1,000 vehicles per day. For bridges that utilize lumber species that require incising to achieve adequate preservative treatment, a modified incising pattern option can now be justified, limiting the impact of the incising factor in the design process. In addition, the use of the impact factor, or dynamic load allowance factor, is not required for timber bridges due to favorable energy absorbing characteristics.
- To improve awareness of modern timber bridges for state and local bridge owners, design aids were developed for three bridge superstructure types: 1) steel stringers with a transverse glulam deck, 2) glulam stringer with a transverse glulam deck, and 3) spike-laminated longitudinal deck. These aids generally included the following information for each

superstructure type: perspective drawing and photographic view, design information, connection detail, crash-tested bridge railing options, and flashing detail options.

- Two demonstration construction projects were completed during this project.
 - In the first project, a St. Louis County construction crew installed a steel girder with transverse glulam deck bridge with a curbless crash-tested railing system. The bridge installation was efficient and new flashing designs were used to direct water off the bridge deck. Despite several challenging site conditions, the project was successfully installed. While the overall project costs were significant, the wood-based materials and labor were similar to that for other alternative designs.
 - In the second project, Hennepin County contracted with a Minnesota construction firm. The previous bridge was removed in December, piles were installed in January, and the timber superstructure was constructed in March. However, spring rains created a long delay in other roadway work and paving, resulting in a delayed opening until July. However, the timber superstructure was completed in approximately five days. The feedback from the county (design engineer, construction engineer, and construction inspector) was positive about all of the timber aspects of the project. This project also was completed at a very difficult site, making a direct cost comparison to alternative designs complicated. However, it appears this project was cost-competitive based on the information collected.
- Time-lapse construction videos (and a multitude of timber bridge-related resources) are available through the National Center for Wood Transportation Structures accessible at: www.woodcenter.org (hosted by Iowa State University).
- Several key details for improving the durability of Minnesota timber bridges were implemented in the bridge construction case studies and/or highlighted within this report.
- The installation of a waterproof asphalt wearing surface is instrumental for the long-term durability of timber bridges. It keeps the roadway portion of the superstructure sheltered from the detrimental moisture accumulation from rainfall and snow. It involves a base layer and a wearing layer of bituminous asphalt with the waterproof membrane sandwiched in between. The waterproof membrane is extended onto the approach roadway to protect the abutment bearings.
- The use of metal flashing is also very important in preventing moisture accumulation at deck edges along the bridge railing systems. For curbless bridge rail systems, flashing components are to be placed prior to installation of the welded steel assemblies for the rail posts and prior to asphalt wearing surface installation. For bridge rail systems with timber curbs, flashing components are to be placed after installation of the bridge railing system but prior to the installation of asphalt wearing surface. In this case, the metal flashing is placed at the inside face of the curbs and on at the bottom and sides of the scupper openings. In all cases, the metal flashing should be extended underneath the outer edge of the asphalt by a minimum of 5 inches.

- When using timber or glulam railing posts, protective post caps are highly recommended to improve the long-term durability of the rail posts. They are placed on top of posts to shelter the exposed end-grain from wetting and drying and from UV-light degradation, both which can cause significant damage over time. Detailed specifications for the post caps are included to ensure proper performance.
- Alternative substructure component options were proposed by the project to improve their performance characteristics. To address common deterioration found in large timber abutment and pier cap members, the use of diffusible borate treatments was suggested as a method to increase their longevity. These offer the advantage of having a more consistent treatment throughout the member instead of just an outer shell of treatment. Another alternative for consideration was the use of steel beam components for the abutment and pier cap members supporting the timber/glulam deck panels. Lastly, the use of a Geosynthetic-Reinforced-Soil Integrated Bridge System (GRS-IBS) was detailed from a separate FHWA demonstration bridge project located in Buchanan County, Iowa. It offers the advantage of a solid foundation while nearly eliminating all approach roadway settlement, which typically occurs at each bridge end.
- Crash-test approved bridge rail systems are required for most timber bridge applications. Several bridge rail systems are currently available for use with timber bridge superstructures primarily for Test Level 2 and Test Level 4 following the evaluation criteria outlined in NCHRP-350. Details for Test Level 2 curbless bridge rails are included for the transverse glulam deck system used in the St. Louis County case study. Details for Test Level 4 bridge rails are included for the longitudinal spike-laminated timber deck system used in the Hennepin County case study. To compensate for larger vehicles and higher speeds introduced in recent years, a new crash-test criterion (MASH, 2016) requirement for bridges was recently adopted by the Federal Highway Administration. Efforts are underway to complete additional full-size bridge rail crash-tests required to meet the new MASH 2016 standards. A research needs assessment was recently completed that set overall priorities for the full-scale crash tests for timber bridge railing to be completed as funding becomes available.
- Despite a negative preception of timber bridges by some engineers and owners, this project clearly shows that there is potential in using timber bridge systems that are capable of being cost-competitive and longlasting. The use of the enclosed design aids can help increase the awareness of modern timber systems that have excellent long-term performance.

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