Economic Design of Bridges on Low-Volume Roads in Southeast Alaska

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The USDA Forest Service in the Tongass National Forest has a unique task in designing bridges for low-volume roads in remote areas of southeast Alaska. This paper focuses on an overview of the methodology for the location, design, construction, and maintenance of these bridges with an emphasis on economics. The site of the bridge is located during planning of the low-volume road. Forest roads have an average daily traffic of less than 50 vehicles per day. A few of the considerations in determining the location of the bridge are preliminary hydrology and hydraulics, stream-bed strata, and environment. Other factors may also control the location and design of the bridge. The bridge is designed after the site has been located. The typical structure is designed for use by a standard U80 logging truck with an L90 yarder overload. The type and size of structure will be based on economics, design life, and environmental limitations of construction materials. The bridge will also be designed with ease of construction in mind. Construction methodology is a major consideration in design because of the remoteness of the area and limited construction equipment. Typical construction materials in southeast Alaska are steel, wood, and concrete. Concrete is not readily available and requires more maintenance with the heavy logging equipment that uses these structures. The last concern is maintenance after the bridge has been completed. The structures should have low maintenance or be easily repaired with limited equipment and resources.

The USDA Forest Service in the Tongass National Forest has a unique task in designing bridges for low-volume roads in remote areas of southeast Alaska. The remoteness of the island archipelago limits the type of structure that can be used and the method of construction for these bridges. The location, design, construction, and maintenance of these remote bridges are of great economic concern with ever-decreasing budgets.

Bridges are the single highest cost items to be built on any road construction project. The cost of one structure can often exceed the construction cost of a mile of road, which is approximately $160,000 per mile in southeast Alaska. Damage done to bridges and major drainage structures such as large pipes greater than 2.44 m (8 ft) from inadequate location, poor design, or poor installation can result in high maintenance costs or structural failures. The loss of a structure can result in major erosion problems, severe economic impacts, and even the loss of human life. The USDA Forest Service, Region 10, Tongass National Forest, Stikine Area, uses the following approach to bridge location, design, economic analysis, construction, and maintenance.

Bridge Location

During initial layout on aerial photographs, the site of the structure crossing is considered a critical control in the planning of the low-volume road. Several issues are concerns in determining the location of a bridge in the field: preliminary engineering, preliminary hydrology and hydraulics, horizontal and vertical alignment, and environmental concerns such as ice flow, stream-bed strata, fisheries, and wildlife.

Preliminary Engineering

The preliminary field location of the bridge should be determined by an experienced road locator with input from internal resource groups and other government agencies. Concerns from agencies outside the Forest Service, such as the Alaska Department of Fish and Game, the U.S. Army Corps of Engineers, and the U.S. Coast Guard, can control where the proposed structure may be located according to regulations and laws. Resource specialists' concerns within the Forest Service also have to be addressed in defining the site location. Intradepartmental resource groups include archaeologists, fishery biologists, wildlife biologists, hydrologists, ecologists, soil scientists, geotechnical engineers, and bridge engineers. Their comments and suggestions help in locating a site that is acceptable to all parties concerned.

Preliminary engineering in the form of site reconnaissance and site drainage analysis is one of the most important items in a bridge site investigation. Analysis should be completed before the site survey to ensure a good design. Topographic site surveys require accurate information about existing highwater marks, current edge of water, bottom of stream bank, top of stream bank, bedrock outcropping, and other important topographical items. The survey should have horizontal and vertical control to the nearest tenth of a foot, and it must include a benchmark and reference points for future construction needs. Stringent procedures will help ensure that the contour map developed, whether by hand or on a computer model, will also be accurate.

Preliminary Hydrology and Hydraulics

Major drainage crossings and other geographical control points are normally located before connecting the crossings with the best location possible. This ensures that the size and number of crossings are kept to a minimum. Preliminary hydrology is completed before field review or site survey if possible. If the contract survey is completed ahead of time, a topographic site survey is conducted on the proposed location, and a site map is constructed from the survey data and used to calculate hydraulics. The hydrology is modeled using three methods: the synthetic hydrograph (L. Bartos, USDA Forest Service), which is valid for drainage areas < 3.88 km^2 (1.5 mi^2); the Water Resource Atlas by Ott Water Engineers, which is valid for drainage areas with a minimum of 2.59 km^2 (1 mi^2); and the R10 FLOWMOD, which is a hydrologic model for estimating ungaged stream flows on the Tongass and Chugach national forests, to determine the drainage area runoff for a 50-year design event. The channel hydraulics are modeled using Mannings equations or the Xspro channel cross-section analyzer by Grant et al.

The flow volumes and correlating elevations from the hydrology and hydraulic programs are then compared, and an educated estimate is made for the 50-year flow and the 50-year highwater elevation. This information and the contour map are taken into the field for a site reconnaissance of the proposed bridge. The site reconnaissance is very important in validating the hydrological and hydraulic models. The bridge engineer needs this experience with the site when designing the bridge in the office. The engineer must consider crossing alignment, roadway alignment, bridge clearances, and channel stability.

Horizontal and Vertical Alignment

The most efficient alignment is achieved when the stream channel and roadway alignment crossing is perpendicular. This is not always possible. If a skewed bridge is required, the skew should be minimized as much as possible to reduce specialized structure costs.

Two major concerns regarding structure location are horizontal and vertical alignment, which depend greatly upon the design speed of the road. Horizontal geometry of the road must be compatible with a straight bridge because of off-tracking of the logging truck's rear wheels. The structure location must provide a short tangent section on both approaches to the bridge to prevent the rear wheels from off-tracking to the inside of the turn and contacting the bridge superstructure. Vertical alignment deals mainly with stopping sight distance (SSD) for sag and crest curves. To reduce the required length of bridge, many bridges designed in southeast Alaska are located in sag curves. Another critical concern with sag curves is the g-force that a fully loaded truck exerts on a structure in the apex of a sag curve. SSD is also the major concern for crest curves as narrow, single-lane bridges require additional sight distance to allow vehicles to be seen.

Environmental and Geological Concerns

Waterway clearances are important to the bridge superstructure to prevent debris or ice damage during high flows. Those at the site should check for signs of damage to nearby trees from floating debris and ice flows. Highwater marks from spring and fall flooding should also be monitored. It is important to consider elevation, snow accumulation, and the location of the drainage basin in relation to northerly or southerly facing slopes relative to spring and fall floods when waterway opening needs are determined. The area of the watershed that will be affected by roads and commercial activities, as well as the associated increase in runoff and debris associated with this development, must also be considered.

If the channel is currently stable, not agrading or degrading, it is important to design a structure that will leave the streambed stable. Scour potential for the structure site and variation with the streambed strata should be considered. The potential for scour typically decreases as the size of the substrate in the stream increases; sand and gravel have the greatest potential for scour, and bedrock has the least. Streambed strata can also help verify the estimated velocity of the stream during flooding. The average size of the material in the stream will help approximate the velocity of the water flowing at peak flows using a chart that plots the relationship of water velocity and stone weight.

Design

After the stream crossing has been determined, design procedure is based on structure type, materials, site requirements and economics, and environmental limitations. Ease of construction and equipment needs are significant during the design procedure.

Structure Type and Size

The type and size of bridge depend on the type of traffic that will use the structure. On the Tongass National Forest, structures are designed for single-lane and double-lane classifications of roadway, and they are often not accessible to public traffic. A timber sale bridge is typically a single-lane 4.88 m wide (16-ft) bridge designed for a U80 logging truck of 72 574.8 kg (80 tons) gross vehicle weight (GVW) (see Figure 1) with an L90 yarder overload of 81 646.6 kg (90 tons) GVW (see Figure 1). The general public bridges are designed for the same loading conditions, but may be one or two lanes wide [4.88 m (16 ft) to 7.32 m (24 ft) wide]. Structure design life is dependent on structure use (i.e., short-term installation of 5 to 10 years or long-term installation of 50 years). If modular structures are used as mobile bridges, site use may be considered as short term for less than 5 years, but actual structure design life will be long term, approximately 35 to 50 years.

Material

Timber, steel, and concrete are used for construction (see Figure 2 for typical bridge cross sections). Numerous design considerations, such as economics, longevity, strength, and span lengths, are used to determine which material type should be used at a specific location.

Timber is broken down into two categories: treated timber and native log stringers. Native log stringers are used for short-term bridges preferably constructed of sitka spruce or yellow cedar that is found on or near the bridge site. If neither species is available, western hemlock can be used, although this will lead to a shorter design life. The spans for these bridges typically range from 9.14 m (30 ft) to 18.29 m (60 ft), with some spans reaching 30.48 m (100 ft). Only high-quality logs may be used to minimize failure because of natural defects. Treated timber bridges, which consist of glulam beams and panelized decks, are long-term structures with spans of up to 36.58 m (120 ft). Currently, wood is cost-effective, but as the price of wood increases, the cost of steel and concrete should be reviewed.

Steel bridges are usually considered long-term bridges when they are painted with a USDA Forest Service Region 10 System 6 paint system. These bridges can be permanent or temporary structures. Permanent steel bridges are plate girder bridges with economical spans from 24.38 m (80 ft) to 36.58 m (120 ft). Bridges that cannot be easily moved after initial installation are considered permanent structures. Modular steel bridges that can be moved with less effort are considered long-term structures and used as temporary or permanent structures. These bridges range in size from 9.14 m (30 ft) to 24.38 m (80 ft); some bridges of up to 33.53 m (110 ft) are being built. Modular bridges are limited by the size and weight of the bridges, as well as the size of equipment available for installation. Modular bridges are usually constructed as half sections, with the two sections bolted together in-place. In contrast, permanent bridges come in many pieces and have to be totally assembled on site. Modular steel bridges are more economical than plate girder bridges because less labor is required on site for construction.

Concrete is seldom used in Southeast Alaska due to cost and handling problems. Concrete bridges can be precast, prestressed beams, or cast-in-place slabs. Precast beams are more economical than cast-in-place slabs, since the price of concrete at a remote site costs as much as \$765 per meters cubed (\$1000/yd^3) in-place. Precast prestressed beams are more economical, but it

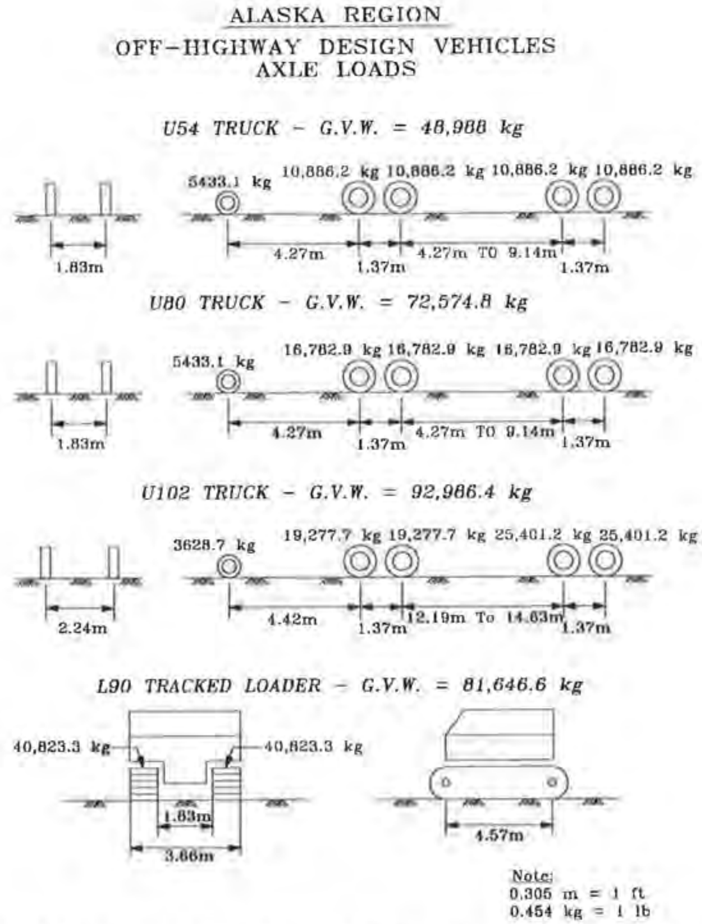

FIGURE 1 Axle loads for off-highway design vehicles in the Alaska region.

is difficult to transport them along low-volume forest roads without damaging them.

Site Requirements

Several factors must be considered in the design of a structure, including debris clearance, alignment, erosion and scour protection, substructure design needs, and span requirements. Debris such as ice flow during spring breakup and floating debris such as submerged logs and stumps that have a potential to cause damage and erosion must be cleared. Horizontal and vertical alignment is required. Scour protection should be designed to reduce or eliminate possible substructure failure, which could eventually result in the total failure of the bridge. This can be accomplished by using a chart that plots the 50-year flood water velocity against the riprap weight and uses this average size as a minimum.

The most important site requirement is substructure design. Without an adequate substructure, the bridge has a high probability of failure. Basic substructures are mud sills, log cribs, gravity wirewalls (i.e., welded wirewalls and geogrid walls), and pile bents with timber lagging for fill containment. Substructure design is site-specific. Span requirements can be single-, double-, and multispan structures. The bridges built in southeast Alaska are typically single spans because of floating debris problems and small drainage system requirements. Midstream pier construction is usually avoided because of erosion problems and associated risks to the superstructure.

Economic Analysis

An economic analysis compares the costs of materials, freight, and installation for superstructure and substructure for equivalent length bridges. All bridges will have a clear span of approximately 15.24 m (50 ft) and be built on mud sills at a site on Kuiu Island in the Tongass National Forest. Costs will be presented for four bridge

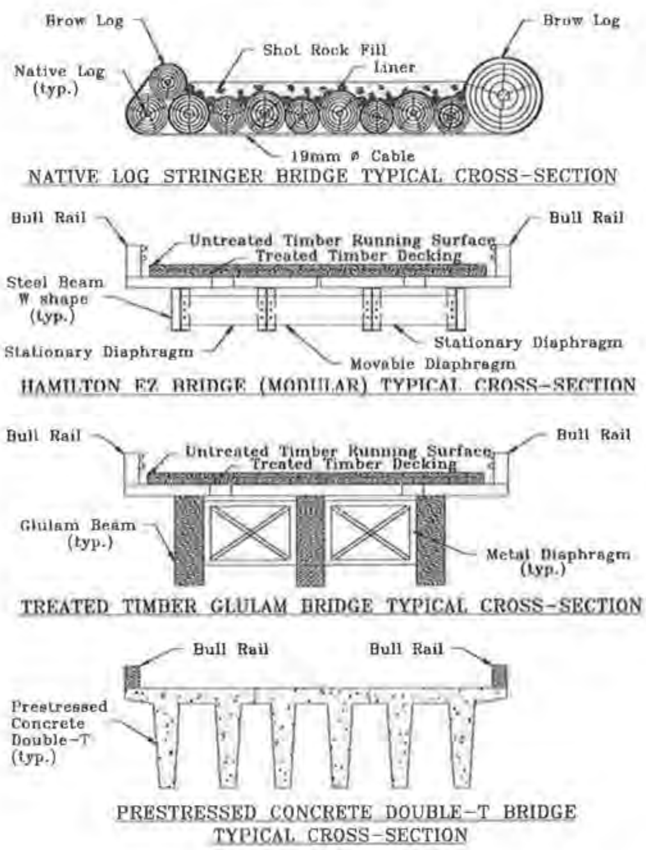

FIGURE 2 Typical bridge cross sections.

types: 15.24-m (50-ft) native log stringer, 14.33-m (47-ft) treated timber glulam, 15.24-m (50-ft) hamilton EZ (modular), and 15.24-m (50-ft) precast prestressed concrete double-T bridge. Plate girder structures are not economical at this site. These costs do not include profit and risk costs and are estimated to be constructed under timber sale contract with no Davis-Bacon wage regulations. Bridges of this length can be built with standard logging equipment; no specialized equipment is required. The excavation process is approximately the same for all four structures and has been neglected in the cost calculations.

Native Log Stringer Bridge

The costs of a native log stringer bridge do not include freight if the log stringers are found at the site. The material costs have a realized value or "stumpage value" of $85/m³ ($200/1000 bf) using Scribner Decimal C Scales to the Forest Service. The current market value for sitka spruce in dimensional lumber is $1060/m³ ($2500/100 bf). Superstructure installation includes placing 10 to .91 m (36 in.) diameter × 15.24-m (50-ft) long stringers with brow logs, wrapping and tightening cables, placing geotextile fabric, and spreading surface rock. Substructure installation includes notching sill longs and setting native log sills. The following calculations apply:

Item	*Cost ($)*	
Superstructure	Stumpage	Market
Materials	8,240	105,250
Freight	n/a	n/a
Installation	2,640	2,460
Superstructure total	10,880	107,710
Substructure		
Materials	250	3,130
Freight	n/a	n/a
Installation	860	860
Substructure total	1,110	3,990
Total cost	11,990	111,600

Treated Timber Glulam Bridge

Freight costs include transport by barge from Seattle, Washington, to southeast Alaska and mobilization to the bridge site. Substructure freight for mobilization to the site is included with superstructure freight costs. Superstructure installation includes setting glulam beams, placing and fastening panelized decking, bullrails, and running planks. Substructure installation includes placing sills, constructing backwalls, and backfilling behind backwalls. The following calculations apply:

Item	*Cost ($)*
Superstructure	
Materials	32,000
Freight	4,940
Installation	7,070
Superstructure total	44,010
Substructure	
Materials	12,000
Freight	730
Installation	4,000
Substructure total	16,730
Total cost	60,740

Hamilton EZ Bridge

Freight costs include transportation from Springfield, Oregon, to Seattle, Washington; transport by barge from Seattle to southeast Alaska; and mobilization to the bridge site. Substructure freight for mobilization to the site is included with superstructure freight costs. Superstructure installation includes setting half sections and bolting them together. Substructure installation includes placing sills, constructing backwalls, and backfilling behind backwalls. The following calculations apply:

Item	*Cost ($)*
Superstructure	
Materials	33,600
Freight	8,400
Installation	3,260
Superstructure total	45,260
Substructure	
Materials	4,200
Freight	320
Installation	4,000
Substructure total	8,520
Total cost	53,780

Precast Prestressed Concrete Double-T

Freight costs include transport by barge from Seattle to southeast Alaska and mobilization to the bridge site. Superstructure installation includes setting concrete beams, grouting keyways, and placing and fastening bullrails. Substructure installation includes placing sills, placing backwalls, and backfilling behind backwalls. Concrete structures are more brittle than timber or steel structures. Therefore, they require twice the time for mobilization. The following calculations apply:

Item	*Cost ($)*
Superstructure	
Materials	33,650
Freight	5,370
Installation	2,740
Superstructure total	41,760
Substructure	
Materials	9,690
Freight	3,170
Installation	1,670
Substructure total	14,530
Total cost	56,290

Cost Comparison for 50-Year Life Cycle

A present-worth cost analysis will be calculated for these four structures for a 50-year life cycle with no assumed salvage value at the end of the cycle. The present-worth method converts future dollars to present dollars. A 4 percent discount rate will be used for the analysis for long-term investments, in accordance with Forest Service policy.

The Hamilton EZ and treated timber bridges will be constructed at year zero, and the running surfaces will be replaced at years 10, 20, 30, and 40 at a cost of $5,000 per redecking. The concrete bridge will also be constructed at year zero and will be redecked at year 25 at a cost of $32,000. The native log stringer bridge will be constructed four times, at years 0, 12, 25, and 37. The following calculations apply:

1. Native Log Stringer (stumpage value)
Cost = −11,990 − 11,990(p/f, 4%, 12) − 11,990(p/f, 4%, 25) − 1,990(f/p, 4%, 37) = −$26,785

2. Hamilton EZ
Cost = −53,780 − 5,000(p/f, 4%, 10) − 5,000(p/f, 4%, 20) − 5,000(p/f, 4%, 30) − 5,000(p/f, 4%, 40) = −$62,023

3. Precast prestressed concrete double-T
Cost = −56,290 − 32,000(p/f, 4%, 25) = −$68,293

4. Treated timber glulam
Cost = −60,740 − 5,000(p/f, 4%, 10) − 5,000(p/f, 4%, 20) − 5,000(p/f, 4%, 30) − 5,000(p/f, 4%, 40) = −$68,983

5. Native log stringer (market value)
Cost = −111,600 − 111,600(p/f, 4%, 12) − 111,600(p/f, 4%, 25) − 111,600(p/f, 4%, 37) = −$249,314

The cost analysis shows the native log stringer bridge to be the best alternative. However, $85/m^3 ($200/1000 bf) is not a realistic value for the price of wood. The value of wood should be greater than the stumpage value, but possibly not as high as the market value. Another problem with native log stringers is availability of stringer. In time, the required high-grade timber for these structures may not be available. The most economical structure is the Hamilton EZ bridge, with a total present-worth cost of $62,023. The present-worth costs for other structures were approximately $6,000 greater than that of the Hamilton EZ bridge. This cost analysis was conducted for a 15.24-m (50-ft) structure, which represents the typical size bridge built in southeast Alaska for stream crossings. Results may differ for longer or shorter span structures.

CONSTRUCTION

The method of construction is a major consideration in the design of the bridge because of the remoteness of the area and the limited construction equipment. The best structures for construction are made of materials that are somewhat forgiving, such as steel and wood. Plans must accurately reflect the site conditions so that the structure is constructed at the designated location as designed. Occasionally, bridges are installed without plans—these eventually fail. Frequently, a change in site conditions will require reassessment of the original design to ensure that the proposed structure is still viable. The last and most important item is to have qualified inspectors on site during construction activities to monitor work and progress. Without adequate inspection, the structure could appear sound but have internal problems that could surface as maintenance problems, shortened structure life, or ultimately structure failure.

Maintenance and Inspection Program

Maintenance after the bridge is complete is the final concern. Structures should be designed and constructed to require low maintenance. Even with a low maintenance structure, a thorough inspection and maintenance program must be developed to ensure the integrity of all bridges. The program should be based on structure type and have an inspection and maintenance frequency not to exceed two years. This strenuous approach will extend the life of bridges. If maintenance is required, the structure will be easily repairable with limited equipment.

Inspection involves reviewing all structure components including the load rating of each structure. The frequency is mandated by National Bridge Inspection Standards (NBIS) to not exceed 2 years. With Native Log Stringers and fracture critical bridges, the frequency may need to be increased to yearly.

The inspections should be conducted by trained personnel familiar with local structure types. Load rating of structures should be completed for all native log stringer bridges more than 5 years old and for all other structures more than 10 years old. Some structures may need to be load rated earlier. Posting structures to ensure safety of contract operators and the general public should be a priority if load ratings indicate such a need.

Conclusion

The procedure for engineering bridges for southeast Alaska is a unique problem that must take many factors into consideration, including location, design, construction, and maintenance. These are important in determining the end product, which is the most economic bridge for low-volume roads in southeast Alaska that meets expected design life requirements.