United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

National Wood
in Transportation
Information
Center

Research
Paper
FPL–RP–593

In cooperation
with the

United States
Department of
Transportation

Federal
Highway
Administration

Timber Bridge Economics

Abstract

Interest in timber bridges has grown rapidly in recent years as a result of new technologies in design and construction as well as advances in material manufacturing and preservative treatments. Despite these advances, little is known about the initial and life-cycle costs of timber bridges relative to those of other construction materials. The objectives of this study were to evaluate the cost characteristics of timber bridges and to compare the initial cost of timber bridge superstructures with that of bridges constructed of steel, concrete, and prestressed concrete. For timber bridges, results show a relationship between cost per square foot and bridge length, load rating, and geographic location. In general, timber bridge superstructures tended to compete with steel and concrete bridge superstructures on an initial cost basis. However, the range in cost per square foot values for all bridges varied widely. This outcome was probably due to both the high variability in these data and the relatively small sample size of the data sets for steel and concrete.

Keywords: Timber bridge, economics, superstructure, cost

April 2001

Forest Products Laboratory and Federal Highway Administration. 2001. Timber bridge economics. Res. Pap. FPL-RP-593. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 40 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53705–2398. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Acknowledgments

This research was funded by the USDA Forest Service under Joint Venture Agreement FP–94–2288 and partially funded by the ISTEA Timber Bridge Research Program. Special recognition is extended to Glade M. Sowards, John Z. Wang, and Blair Orr, Michigan Technological University. We also thank Don Czarniewski, Julie Lyons, and Melissa Mielke, Michigan Technological University, for their assistance on this project. We express appreciation to the following individuals from the USDA Forest Service, Forest Products Laboratory: Kim Stanfill–McMillan for project guidance and assistance in developing the data questionnaire; Paula Hilbrich Lee for project guidance and assistance in preparing the report; Steve Verrill for reviewing the data analysis and providing valuable input pertaining to the statistical results; and the Information Services Team for assistance in preparing the report.

Contents

Timber Bridge Economics

Introduction

Approximately 200,000 bridges throughout the United States are deficient; costs of replacement are estimated at $84 billion (Smith and Bush 1994). In the face of such staggering figures, it is obvious that a substantial need has developed for new economical bridges. In recent years, interest in timber bridges as one solution to the deteriorating infrastructure has been rapidly increasing. To a great extent, this rise in interest is due to new technologies in design and construction and advances in material manufacturing and preservative treatments.

Throughout much of the 19th century, timber structures accounted for the majority of bridges and trestles in the United States. These structures were constructed of sawn lumber, and many lacked proper preservative treatments to protect against exposure to moisture and subsequent decay. In addition, older timber bridges were often crudely designed, with little or no input from engineers. It was not until 1840 that a complete stress analysis of a timber bridge design was included with the bridge designer's patent (Ritter 1990). In the 20th century, timber bridges began to be replaced by steel. By 1910, steel competed with timber as a bridge construction material on a first-cost basis, and by 1930, steel dominated the bridge market (Ritter 1990).

The failure of older, primitive timber bridges and their eventual replacement first by steel and later by concrete is the likely source of a general perception held by some people that timber bridges are inferior in quality. Over time, however, the limitations of steel, concrete, and prestressed concrete have become apparent. These limitations range from susceptibility to corrosion to costly maintenance and replacement.

In the mid-1940s, engineers began to reconsider timber for bridge construction. Later, the development of techniques such as glue- and stress-lamination demonstrated the strength of timber as a construction material, which promoted interest in timber bridge utilization (Ritter 1990). The rationale for this interest is threefold. First, timber may offer a low-cost alternative to other bridge construction materials such as steel, concrete, and prestressed concrete. Second, recent research indicates that timber bridges may be more durable than those constructed from other materials, particularly in cold climates where salts and other de-icing agents are frequently used. Third, it is hoped that the creation of a viable timber bridge market will encourage economic growth in rural areas with underutilized timber resources.

As part of the renewed interest in timber bridges, Congress passed legislation known as the National Timber Bridge Initiative, now called the Wood in Transportation Program (WIT), which began receiving funding in Fiscal Year 1989. The program was established to help diversify local economies by "improving rural transportation networks, expanding the range of markets for wood products, and creating service industries for wood bridge construction" (USDA 1994). Since its introduction, WIT has resulted in more than $17 million in congressional funding for bridge research, construction, and technology transfer (Smith and Bush 1994). In addition to the WIT program, in 1991 Congress included provisions for timber bridge research and a demonstration program in the Federal Highway Administration Intermodal Surface Transportation Efficiency Act (ISTEA). The ISTEA provided $50 million for a 6-year program. As a result of such efforts, modern timber bridge designs, construction techniques, and preservative treatments have made it possible to improve the utilization of local wood species that were previously viewed as not marketable.

Despite this renewed interest in timber bridges, little is known about their initial and life-cycle costs relative to those of bridges constructed from other materials. Such information is critical to convincing transportation agency officials that timber bridges are a viable alternative to bridges made of other materials.

Background

In recent years, several studies have been conducted on the subject of timber bridge economics. The stated impetus for the bulk of these projects is the need for cost-effective alternatives to traditional infrastructure components of the national highway system. Most of this research tends to (1) focus on bridge superstructure, (2) group all timber bridges together, (3) address initial costs as opposed to life-cycle costs, (4) be limited to a certain geographical area, (5) rely on estimated costs, and (6) lack statistically significant data.

Most studies focus only on bridge superstructure, which includes the deck, beams, girders, wearing surface, and periphery such as guardrails. Researchers have found that substructure construction costs are more likely to vary with respect to the site as a result of differences in geological formations, soil types, and other site-specific characteristics that are difficult to quantify. For example, Behr and others (1990) considered only superstructures in their cost comparison of several bridge designs in the New England area.

Similarly, Verna and others (1984) limited their treatment of bridge replacement costs to major superstructure components.

Studies that compare timber bridges with bridges made from other materials tend to group all types of timber bridge designs together. However, timber bridges are not uniform. Timber deck bridges should be compared with prestressed concrete slab bridge designs and timber girders to steel girders, for example.

Research efforts tend to focus on initial costs as opposed to life-cycle costs. Some studies rely on estimates of expected life as a rough indicator of life-cycle costs. There is some question as to the need for more than initial cost information, because such costs represent only a portion of bridge costs over time. According to Wolchuk (1988), the immense task of rebuilding the nation's bridges "should call for planning based on sound economic principles, with due consideration of the total cost of structures over their entire projected service lives." A review of maintenance and cost data by Hill and Shirole (1984) suggests that timber bridges with less than 30 years of service have few major problems. However, most researchers cite difficulty in obtaining accurate, complete maintenance and replacement cost figures as the main reason for omitting life-cycle cost analyses.

Studies tend to be limited to a particular State or geographic region or are area specific. For example, because the *Cost Comparison of Timber, Steel, and Prestressed Concrete Bridges* by Behr and others (1990) applies to only potential bridge projects in New England, the results may not be entirely applicable in other regions. Verna and others (1984) and Hill and Shirole (1984) worked with similarly small geographic areas in Pennsylvania and Minnesota, respectively. Sarisley (1990) considered a single prototype stress-laminated timber bridge in Connecticut, thereby restricting the results to region and structure type. Such limitations create difficulties in applying the conclusions of past research to current bridge project proposals.

Some research efforts rely on estimated compared with actual cost information. For example, in a study by Behr and others (1990), cost information was obtained by supplying participating contractors with a bridge design and asking each to provide an estimated bid. In another study (Verna and others 1984), bids were supplied for various deck replacement materials and designs. Despite its appeal from a data collection standpoint, this approach does not allow for potential cost overruns and may serve to skew cost comparison results.

A final characteristic of past research is a lack of statistically significant databases necessary to make valid comparisons between the costs of various bridge projects. As Behr and others (1990) note with regard to their own study, this problem stems from sample sizes that are too small for the application of meaningful tests of statistical significance.

Table 1—Summary of timber bridge costs from four major studies

Study	Superstructure cost ($/ft^2)	
	Mean	Median
Behr and others 1990		
20 ft	—	46.12
40 ft	—	47.12
60 ft	—	57.87
Hill and Shirole 1984[a]	29.78	—
Sarisley 1990[b]		
Single lane	68.00	—
Two lane	52.00	—
Verna and others 1984[c]		
Case I	37.00	—
Case II	57.00	—

[a] Calculated from weighted average of structure cost per square foot from State and non-State routes in Minnesota. Component costs are not indexed for inflation.

[b] Single-lane cost is the actual cost from the bridge project. Researchers used single-lane costs to estimate two-lane costs.

[c] Represents costs from two bridge replacement projects in western Pennsylvania.

Table 2—SI conversion factors

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeters (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.093	square meter (m^2)

Table 1 summarizes mean and median timber bridge costs per square foot from four major studies. (See Table 2 for metric conversion factors.) As Table 1 indicates, results of past studies are varied and, at times, contradictory. Three of these studies (Behr and others 1990, Verna and others 1984, and Hill and Shirole 1984) suggest that timber bridges are cost competitive with bridges composed of other materials for certain applications or within limited specifications, such as length and load rating.

However, there appears to be no consistent pattern between studies as to the limits or characteristics of timber bridge feasibility. For example, Behr and others (1990) found a positive relationship between cost per square foot and span length, whereas Verna and others (1984) found an inverse correlation. Further clarification of timber bridge cost relationships is needed.

Objectives and Scope

The objectives of this study were to evaluate the cost characteristics of timber bridges and to compare the initial cost of timber bridge superstructures with that of bridges constructed of steel, concrete, and prestressed concrete. Where possible, the intent of this project was to overcome the limitations of past research efforts, as summarized in the Background.

For this study, vehicular bridges, located throughout the United States, were load rated in accordance with American Association of State Highway and Transportation Officials (AASHTO) recommendations. This wide scope implies practical, generally applicable results. Cost data were taken from the June 1994 National Bridge Inventory (FHWA 1994). Cost information was gathered from completed, non-demonstration bridge projects constructed during and after 1980. Non-demonstration bridges are those bridges constructed outside WIT and/or ISTEA timber bridge demonstration programs.

The study included both single- and multiple-span bridges. Because of the wide scope, some bridges of the same length have a different number of spans, thus different cost characteristics. Because of the potential variability of substructure costs with respect to site-specific conditions, such as differences in soil composition and terrain between bridge sites, the study focused primarily on superstructure costs. As a result, the bridge cost information pertains to superstructure cost per square foot, not total cost, unless otherwise stated. In addition, only initial cost was evaluated because there were inadequate data for a meaningful comparison of life-cycle costs. This is partially due to the fact that modern bridges have needed little repair. Most of the study bridges were constructed during or since 1980. Typically, long-term cost data are available only for bridges of antiquated design and construction.

Research Methodology

The research methodology consisted of data collection and data analysis. The section on data collection presents the methods used to obtain usable bridge cost information. The section on data analysis describes the analyses performed to interpret project data.

Research efforts were continuous over the duration of the study. Data collection and analytical procedures often overlapped because of the limited availability of the timber bridge cost data and the limits placed on matching timber and nontimber bridges. It was possible to match the bridges only after the timber bridge data had been received and analyzed. The flowchart in Appendix A illustrates the project methodology in chronological order. Research stage numbers are provided for cross-referencing the flowchart with the body of this report.

Data Collection

Data collection procedures are described for timber and matched bridges. Limitations on the availability of data are also discussed.

Timber Bridges

The first step in the data collection process was to identify timber bridges throughout the United States that fit within the scope of the project. The June 1994 U.S. Department of Transportation Federal Highway Administration National Bridge Inventory (NBI) (FHWA 1994) was obtained to accomplish this task. This database contains structural and inspection statistics for 668,433 bridges and other highway structures across the United States that are more than 20 ft long. The NBI contains information for each bridge record, such as identification or structure number, location, ownership, length, width, number of lanes, and year built, as well as inspection information on structural condition; there are 116 data fields. The NBI database is updated regularly (FHWA 1988).

Thirty-six of the 116 NBI database fields were retained for this study (Table 3). Among these were the State, county, place, structure number, location, feature intersected, structure length, maximum span length, deck width, number of lanes, load rating, and year of bridge construction.

The database was filtered to eliminate bridges that fell outside the scope of the project (see App. A, Stage 1). Records were maintained only for load-rated bridges constructed during or after 1980. This year was selected as being late enough to emphasize modern timber bridges, yet early

Table 3—NBI database fields used for study[a]

Database field	Database field
State code	Design load (rating)
State Highway Dept. Dist.	Bridge status (open, posted, closed)
County (Parish) code	Type of service
Place code	Structure type, main
Record type	Number of spans, main
Route signing prefix	Maximum span length
Level of service	Structure length
Route number	Bridge roadway width
Directional suffix	Deck width
Features intersected	Deck condition
Facilities carried	Deck structure type
Structure number	Deck protection
Location	Superstructure condition
Milepoint	Substructure condition
Maintenance responsibility	Operating rating
Owner	Wearing surface
Functional classification	Membrane type
Year built	
Lanes on or under	

[a]Thirty-six of 116 NBI database fields were used.

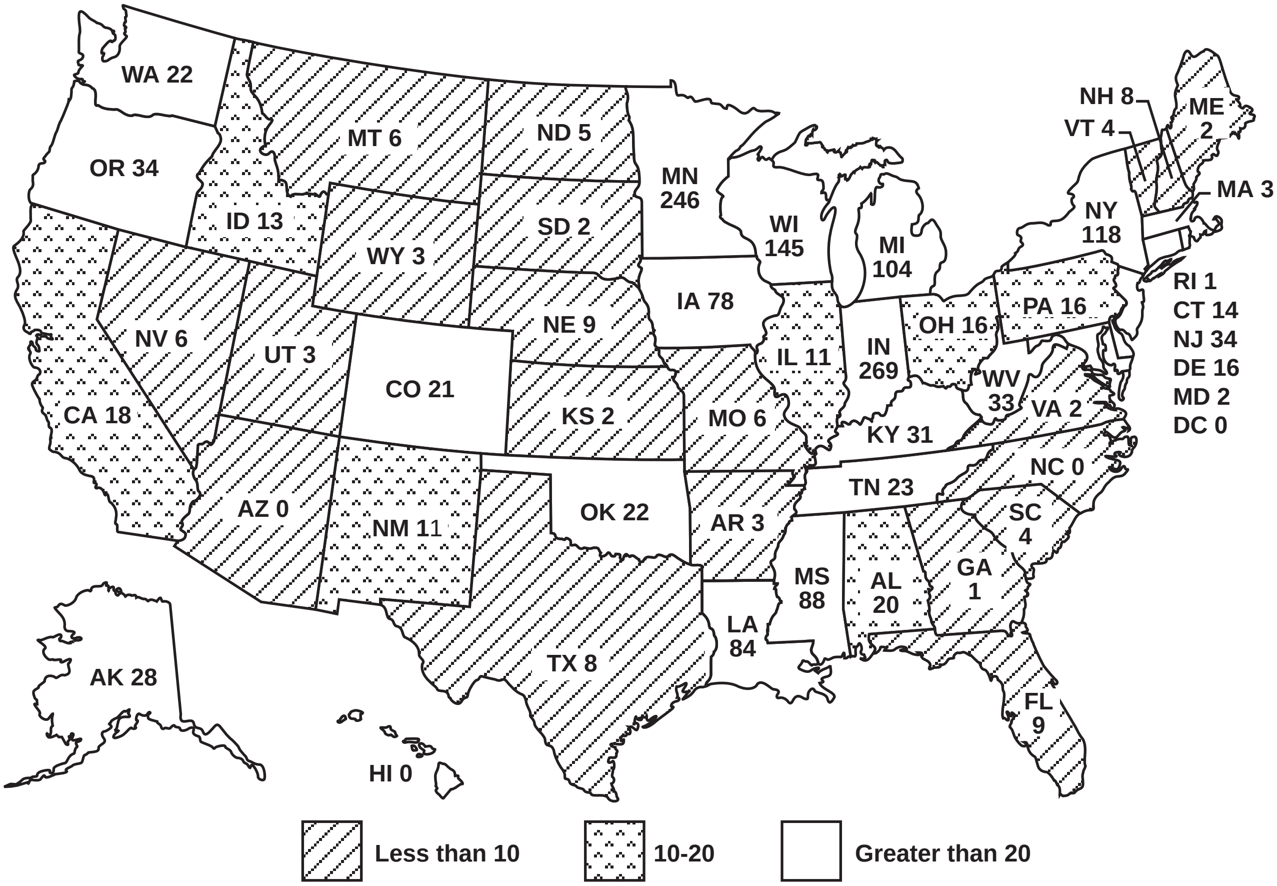


Figure 1—Geographic distribution of load-rated vehicular timber bridges constructed during or after 1980.

enough to allow for a large data set. The database was also scanned to remove records representing pedestrian and railroad bridges. The resulting timber bridge database contained information for 1,604 highway bridges. Figure 1 shows the geographic distribution of timber bridges meeting the project requirements.

An owner-agency was identified for each bridge record using ownership information and State and county code numbers supplied in the NBI database (FHWA 1994), the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA 1988), and the *Codes for Named Populated Places, Primary County Divisions, and Other Locational Entities of the United States and Outlying Areas* (National Bureau of Standards 1987).

Addresses and contacts were found for each owner–agency and incorporated into the project database. This information was primarily requested from the Department of Transportation or other central transportation office in each State. In some cases, the owner–agency is the State transportation offices. In most instances, the owner–agency is a county; the address and contact of this type of owner–agency was obtained from the pertinent State transportation office. Similar information was obtained from the National Park Service and USDA Forest Service offices, and the appropriate agency contacts were linked with each bridge.

The next step in the data collection process was to develop a questionnaire to obtain cost information from each timber bridge owner–agency. A background literature review was conducted to determine the best information to request, and a detailed 2-page survey was developed to obtain cost, bid, and contractor or supplier information (App. B). This questionnaire provided information to aid transportation officials in bridge identification. Owner–agency personnel were asked to review the information and report any discrepancies.

Three cost figures were defined and solicited: (1) total superstructure cost, (2) total substructure cost, and (3) total bridge cost. Superstructure costs included materials, labor, and transportation expenses associated with the construction of all bridge components between abutments and above bents, including stringers, beams, deck, traffic railing, and wearing surface, and costs of protective membrane and excluding approach, approach railing, detour, and mobilization. Substructure costs were defined as materials, labor, and transportation expenses associated with the construction of all bridge components beneath the superstructure, including abutments and bents, and costs of excluding approach, approach railing, detour, and mobilization. Bridge costs included all materials, labor, and transportation expenses associated with the completion of the entire bridge project, with the exception of approach, approach railing, detour, and mobilization costs.

Additional information was requested regarding factors that might skew cost figures, such as the inclusion of a given bridge in local, State, or Federal demonstration projects, such as the Timber Bridge Initiative, or volunteer/donated labor, materials, or services in bridge construction. In addition, a cost worksheet was provided to aid in superstructure cost tabulation; a copy of the final project cost worksheet was requested for verification purposes. Agency officials were also asked to list the number of bids placed for the bridge project in question. Finally, the name, address, and telephone number of the primary contractor and/or supplier of superstructure materials for the bridge in question were requested, to aid in verifying cost figures. The questionnaires were mailed to respective bridge owner–agencies across the United States.

After the timber bridge questionnaires were received, any new bridge data obtained from owner–agencies were entered into the timber bridge database. Where discrepancies were noted by a transportation official regarding variables such as bridge length, year built, and location, corrections were made based on the comments written on the questionnaire. Other than those corrections, the timber bridge database was not altered. Those records containing superstructure cost were identified as valid or usable timber bridges. Throughout the remainder of this report, bridges for which usable superstructure cost information was available are referred to as “valid” bridges. All cost evaluations and comparisons for this study were based on valid bridges only.

Matched Bridges

To execute a useful cost comparison between timber and nontimber bridges, a matching scheme was developed for pairing each valid timber bridge with a steel, concrete, and prestressed concrete bridge possessing similar characteristics. Although exact matches of all characteristics were unlikely, it was expected that matches of quantitative characteristics, such as bridge width and length, would occur within an acceptable range. In the same manner, exact matches of discrete characteristics, such as load rating and location, were expected.

Based on these assumptions, a bridge “match” existed for a given timber bridge if both bridges were located within the same State, were within 15% in structure length, had the same number of lanes, had the same load rating, and were built within 15 years of the year of construction of the timber bridge in question. This set of criteria is referred to as the primary matching scheme throughout the remainder of this report. The ranges were believed to be precise enough for comparison while broad enough to allow a suitable number of matches.

Using the NBI, up to 10 matching bridges of each material type (steel, concrete, and prestressed concrete) were identified for each timber bridge. In cases where more than 10 matching bridges of a particular material type were identified, only the 10 bridges closest in length to the original timber bridge were selected; 2,549 matching bridges were identified as valid timber bridges (App. A, Stage 2).

The questionnaire distributed to timber bridge owner–agencies was then distributed to owner–agencies of the matching steel, concrete, and prestressed concrete bridges (App. B). Bridges for which the completed questionnaires contained information on superstructure cost or a final contractor or bid worksheet by which such costs could be obtained were identified as valid or usable matched bridges.

The study included both single- and multiple-span bridges. In addition, it was possible for two bridges of the same total length to have a different number of spans, thus different cost characteristics. For example, a 36-ft-long bridge consisting of two, 18-ft spans would have different superstructure design requirements than a bridge with a single 36-ft clear span. Structural members typically increase in size as span length increases to withstand applied bending and shear stresses and meet deflection criteria for a given design load (Ritter 1990). Thus, a relationship between cost and span length is likely because a greater volume of primary construction material is generally required as span length increases to meet design criteria.

Because superstructure cost might be influenced by span length, bridges matched through the primary matching scheme were additionally screened to within 15% of maximum span length (secondary matching scheme). Bridges that did not meet the maximum span-length criterion were identified for further analysis (App. A, Stage 4).

Project Data Limitations

The availability of bridge cost information was limited for some portions of the Nation. For various reasons, some transportation agencies were unable or unwilling to provide cost information for timber and nontimber bridges under their jurisdiction. Many agencies responded by stating that they did not maintain the type of detailed information requested on the questionnaires. Some agencies were too busy or short-staffed and were unable to respond to the survey. Others had already developed an opinion regarding the use of timber bridges and were unwilling to respond. These data limitations precluded taking a smaller random sample, since such samples rely heavily upon high response rates. Instead, a large body of data was collected, where available, through an intensive survey. Reporting was self-selecting and not randomly drawn.

In an effort to establish a representative sample, multiple mailings were sent to bridge owner–agencies to increase response rates. In some cases, follow-up phone calls were made to obtain data and/or ensure accuracy of information. In addition, project response characteristics were compared or verified with those of the total populations of project bridges. This assessment is discussed further in the following section on data analysis. Considering these efforts and the broad scope of the study, it is likely that the results of this project are generally applicable to timber bridge construction.

Data Analysis

Data analysis procedures are outlined for verification of responses, timber bridge cost characteristics, and cost comparison. The section on verification of responses describes the steps taken to compare response data characteristics with those of the total population for both timber and nontimber bridges. The section on timber bridge cost characteristics details the manner in which timber bridge cost characteristics were evaluated. Finally, the section on cost comparison describes the procedures by which timber and nontimber costs were compared.

Verification of Responses

To ensure that a representative sample of the population was surveyed, valid bridges were compared with those from the total population (App. A, Stage 3). Specifically, the percentage of bridges from the valid data set possessing a given characteristic was evaluated against the percentage of bridges from the total population possessing that same characteristic. For example, the percentage of bridges with an HS20 load rating was compared with the percentage of the total population of bridges with this load rating. This analysis was completed for both timber and matching bridges for seven factors: construction type, structure length, deck width, number of lanes, load rating, year constructed, and geographic region.

Timber Bridge Cost Characteristics

The cost figures for each timber bridge were indexed for inflation based on the year of construction and the construction sector producer price index (PPI) from *The Economic Report of the President: 1996* (Council of Economic Advisers 1996) (Table 4). The PPI is an indicator of the cost of a given set of goods at the point of the first significant commercial transaction and is appropriate for gauging changes in the construction market where raw materials and semi-finished goods are utilized. Bridge costs were indexed around the base year 1982 by dividing cost figures by the PPI percentage for the year in which the bridge was constructed. The index year is a scalar, and the choice of year does not change the results. The year 1982 was selected because it is the baseline used in *The Economic Report of the President: 1996.* By using that index year, it was not necessary to transform the indexes in this report. Prices were indexed to control for inflationary price changes not directly associated with events occurring in the bridge construction market. Any trend in bridge construction after indexing was likely the result of developments in the market.

Table 4—Construction sector producer price indexes (PPIs) used to adjust timber bridge costs for inflation

Year bridge constructed	PPI
1980	91.3
1981	97.9
1982	100.0
1983	102.8
1984	105.6
1985	107.3
1986	108.1
1987	109.8
1988	116.1
1989	121.3
1990	122.9
1991	124.5
1992	126.5

Timber bridge cost data were analyzed on a unit or per square foot basis for six factors: construction type, structure length, maximum span length, load rating, year of construction, and geographic region. Cost per square foot was compared with the continuous factors of structure length, maximum span length, and width. The data set was not random but self-selected by respondents. For this reason, no attempt was made to fit a regression line to these plots nor were statistical tests performed. Box plots were developed for comparisons between cost per square foot and categorical factors (construction type, load rating, year constructed, and region).

Cost data were additionally analyzed across multiple factors or disaggregated. Such a data cross section allows for a clear understanding of the relationship between two variables while holding other factors constant.

Because of the limited number of single-lane structures and in an effort to further disaggregate project data, only two-lane structures were considered in this stage of analysis. Bridges were separated by construction type. Because of data limitations, only the two most common construction types were retained at this analysis stage: the slab and stringer/multi-beam.

Data sets from both slab and stringer/multi-beam construction types were subdivided by region. The two largest regions, Midwest and Northeast, were used to create box plots showing cost per square foot by load rating. The process was then reversed. This time, the slab and stringer/multi-beam data sets were additionally subdivided by load rating and analyzed by region. The two largest load-rating data subsets, HS20 and HS20+Mod, were used to develop box plots showing cost per square foot by region.

Plots of cost per square foot as a function of structure length were also developed. Such plots were created for HS20 and HS20+Mod bridges in each of two regions (Midwest and Northeast) for both slab and stringer/multi-beam construction types, for a total of eight plots.

Cost Comparison

A preliminary cost comparison was made based on all available data points for each bridge material. A box plot was developed using the complete valid data set for each material to compare median values and distribution characteristics based on the maximum number of observations available (App. A, Stage 5a).

For a more informative comparison, valid bridges of each material type were linked to their respective timber bridge match (App. A, Stage 5a). The cost per square foot for each matching bridge was adjusted for inflation based on the construction sector PPI. As Figure 2 shows, mean cost per square foot (N_{ij}) was calculated according to

$$N_{ijt} = \sum_{t=1}^{k} \frac{N_{ijt}}{k}$$

where

N_{ij} is the mean of nontimber bridge(s) of type j that match bridge i,

i an index for the set of timber bridges,

j the matching bridge type, where j = s, c, and p for steel, concrete, and prestressed concrete, respectively,

k the number of bridges for matching bridge type j that match timber bridge i, and

N_{ijt} the adjusted cost for nontimber bridge t ($t = 1, \ldots, k$), of type j, that matches timber bridge i

in the case of multiple responses (questionnaires) for bridges of the same material type for a given timber bridge. As a result, only one cost per square foot value per material type was matched with that of each timber bridge (App. C).

The matched bridges were divided into three groups of matched pairs: timber and steel, timber and concrete, and timber and prestressed concrete bridges. The size of each group depended on the number of timber bridge–nontimber bridge matches per material type.

The individual differences between each timber bridge and its nontimber match (d_i) were calculated:

$$d_{ij} = T_i - N_{ij},$$

where T_i is timber bridge i adjusted superstructure cost per square foot.

Note that for simplicity, $d_{ij} = d_i$ and $N_{ij} = N_i$ throughout the remainder of this report.

Individual differences (d_i) and median differences (m_d) were plotted in box plots. Positive differences (d_i) resulted when timber bridge cost per square foot values were greater than those for their nontimber matches, and negative differences (d_i) resulted from timber bridge cost per square foot values less than those for their nontimber matches.

This process was repeated for the subset of bridges matched by the secondary matching scheme, which was governed by a stringent maximum span length criterion (App. A, Stage 5b).

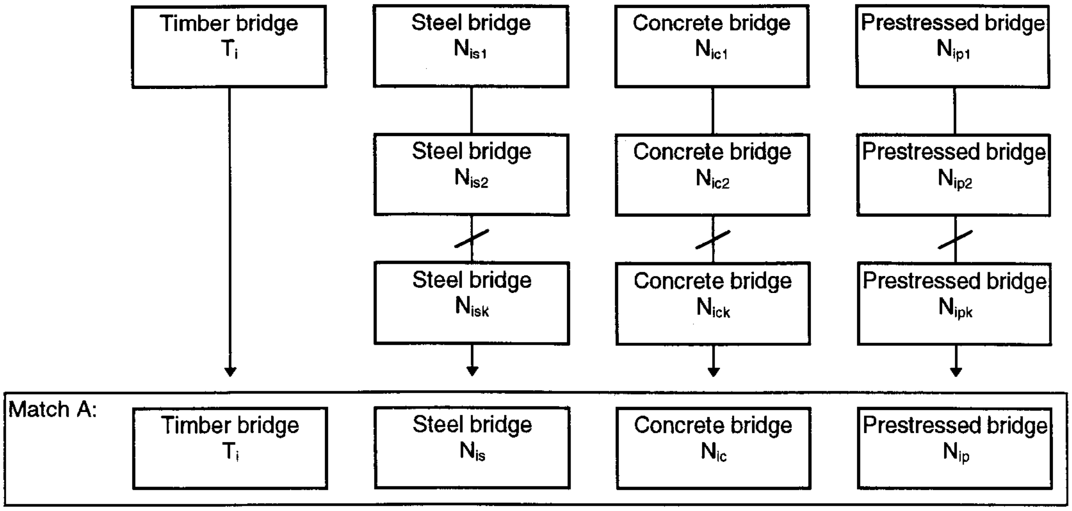


Figure 2—Calculation of mean cost per square foot for nontimber bridges.

Results and Discussion

Characteristics of timber bridges in the valid data set are listed in Appendix C. To verify that these data were representative of the total population of timber bridges, bridges in the valid data and total population sets were compared by construction type, structure length, structure width, number of lanes, load rating, year constructed, and region (App. D). A trend was identified between the valid and total population sets for size-related data categories. The data on structure length, structure width, number of lanes, and load rating all demonstrate an underrepresentation of small bridges with low load ratings and a slight overrepresentation of larger bridges with higher load ratings. Furthermore, the figure of valid data set responses by region (App. D, Fig. 12) suggests an underrepresentation in 5 of the 10 regions, including the large Southeast region, and an overrepresentation in the Midwest and Northeast regions. However, given the wide scope of this project and the overall consistency between the valid and total population sets for the factors considered, it is likely that the findings of this report will be broadly applicable to timber bridge construction.

Cost Characteristics for Timber Bridges

The cost analysis of timber bridge superstructures is described in terms of cost characteristics by single factors and across multiple factors. Data on cost trends evaluated for construction type, structure length, maximum span length, load rating, year of construction, and geographic region are shown in Appendix E. Continuous factors are plotted against cost per square foot. Categorical factors are described by box plots. Data are also disaggregated to show trends across multiple factors.

Single Factors

Although measures of central tendency, such as median and mean, are useful in summarizing cost data, more complete understanding of bridge costs can be obtained by comparing costs against other factors, such as length and load rating. The sole use of measures of central tendency often hides important information about data. For example, costs could be greater for one construction type than for another. Considering median or mean timber bridge cost per square foot alone would not reveal such information. Therefore, it is useful to compare timber bridge cost per square foot with other factors.

The highest median costs for T-beam, box beam multiple, and truss-through bridges were well above \$50/ft^2 (Table 5). It is not known whether the unusually high cost of a single-lane frame timber bridge is representative of frame bridges because of the single observation in this category. In terms of structure length, cost was greater at both ends of the spectrum (between 20 and 50 ft long and greater than 150 ft long). In terms of bridge span length, costs were highly variable; the maximum span length of most bridges was less than 50 ft.

Table 5—Bridge cost by construction type

Construction type	Observations (no.)	Cost (\$/ft^2)	
		Median	Mean
Slab	138	24.83	28.58
Stringer/multi-beam	56	31.12	31.59
Girder and floorbeam system	1	45.25	45.25
T-Beam	2	64.10	64.10
Box beam or girder			
Multiple	7	56.00	57.80
Single or spread	1	51.69	51.69
Frame	1	149.50	149.50
Truss, through	2	60.18	60.18
Arch, deck	1	39.09	39.09
Total	209		

No pattern emerged for the relationship between superstructure cost and bridge width. In some timber bridge designs, an increase in deck width not only requires an increase in material but also influences deck and/or floor beam thickness. In such cases, the volume of bridge material must increase as deck width increases to maintain a given load rating. In addition, some deck designs require transverse bracing, stiffener beams, or other components as width increases (Ritter 1990). Consequently, bridge width may influence superstructure cost even when cost is considered on a per square foot basis. Nevertheless, the effect of width on superstructure cost showed wide variation in our valid data set. It is likely that the cost effects of bridge width were obscured by other cost factors.

Because bridges built to carry high loads may require more primary construction material per square foot of deck, it is likely that load rating is an important cost factor. All seven load classifications were present in the valid data set. However, few data were available for the H10, H15, HS15, and HS25 load ratings (Table 6). This shortage followed the general trend in the total population, with the majority of bridges falling in the H20, HS20, and HS20+Mod classifications. Cost tended to increase with load rating, except in the H10 and HS15 categories (Table 6). However, as Table 6 indicates, the HS15 category was represented by only one data point. In addition, an unusually high value for one bridge in the H10 category dramatically influenced the mean cost for that load rating. This was an atypical one-lane frame timber bridge in Mississippi. The elimination of this outlying observation lowered the mean cost for the H10 category from \$52.41 to \$20.05.

Table 6—Bridge cost by load rating

Load rating	Observations (no.)	Cost ($/ft^2)	
		Median	Mean
H10	4	27.70	52.40
H15	7	7.87	14.75
HS15	1	46.92	46.92
H20	9	20.03	21.67
HS20	154	25.48	30.34
HS20 + Mod	37	35.56	40.44
HS25	3	39.09	37.83
Total	215		

Median cost per square foot was consistent across construction years (Table 7). Because cost values were indexed for inflation, any observable cost trend over time was likely the result of developments in the timber bridge construction market or related markets. Thus, there appeared to be no identifiable relationship between cost per square foot and year of construction.

Superstructure cost varied across regions and was particularly variable in the Southeast (Table 8). The mean cost for the Southeast was apparently skewed upward by the same unusually high cost per square foot noted for the H10 load rating.

Multiple Factors

Just as evaluating timber bridge cost data against other factors provided a clearer understanding of timber bridge cost characteristics, evaluating timber bridges for costs across multiple factors allowed for an even closer look at cost relationships. We compared costs of two types of two-lane timber bridges, slab and stringer/multi-beam. For each construction type, costs were compared for each region (Midwest and Northeast) by load rating and for each load rating by region; costs were also compared in relation to structure length (App. E).

For both the Midwest and Northeast, costs were higher for HS20 bridges than for HS20+Mod bridges, the two load ratings most represented in these data. Costs were lower in the Midwest for both types of bridges. Costs were highest for short bridges, somewhat high for long bridges, and lowest for middle-length bridges. In both regions, cost values for the HS20 and HS20+ load ratings were widely variable across structure lengths.

In the Midwest, the median cost of two-lane stringer/multi-beam timber bridges increased as load rating increased. The same trend was evident in the Northeast, except for the HS15 category. When evaluated by region, cost of the HS20 two-lane stringer/multi-beam timber bridges was lowest in the Midwest, higher in the Northwest, and highest in the Northeast. For the HS20+ bridges, which were evaluated in two regions, median costs were higher in the Midwest than in the Northeast but mean costs were reversed.

Table 7—Bridge cost by year of construction

Year constructed	Observations (no.)	Cost ($/ft^2)	
		Median	Mean
1980	21	32.41	31.85
1981	13	21.53	21.26
1982	12	23.12	31.67
1983	8	28.20	36.49
1984	12	22.58	25.00
1985	21	26.96	29.54
1986	21	23.87	25.04
1987	14	25.19	30.98
1988	18	25.93	29.14
1989	13	28.37	32.26
1990	30	29.91	40.28
1991	24	35.33	36.40
1992	15	36.47	36.36
Total	222		

Table 8—Superstructure cost by region

Region	Observations (no.)	Cost ($/ft^2)	
		Median	Mean
Central	5	36.98	34.69
Intermountain	1	46.58	46.58
Midwest	148	24.28	27.81
Northeast	54	36.61	42.21
Northern	2	28.79	28.79
Northwest	7	28.76	30.06
Southeast	5	4.80	37.00
Total	222		

Summary of Timber Bridge Costs

In general, data received from owner–agencies were highly variable, making it difficult to identify relationships between factors.

When costs were compared for one factor, we note the following:

- Cost per square foot varied by construction type, with the lowest mean and median values reported for slab and stringer/multi-beam timber bridges, the most widely constructed types.
- When plotted against structure length, cost per square foot exhibited a parabolic shape, with higher values for the shortest and longest bridge lengths.

- Neither maximum span length nor bridge width appeared to influence cost per square foot.
- Year of construction had little effect on cost per square foot.
- Cost per square foot increased with higher load ratings, with noted exceptions.
- Midwest, Northern, and Northwest regions had lower median costs per square foot than those reported for Central and Northeast regions. Cost data varied widely for the Intermountain and Southeast regions.

When costs were compared across multiple factors, we note the following:

- Disaggregating superstructure cost information across multiple factors improved our understanding of cost relationships between factors.
- Across multiple factors, timber superstructure cost per square foot was higher for the Northeast region than for the Midwest region.
- Cost per square foot was higher for the HS20+Mod load rating than for the HS20 load rating across multiple factors.
- A comparison of cost per square foot and structure length exhibited a parabolic shape for HS20 two-lane slab timber bridges in the Midwest region.
- A comparison of cost per square foot and structure length displayed a parabolic shape for HS20 two-lane stringer/multi-beam bridges in the Midwest region.
- Even with substantial disaggregation, all plots of cost per square foot compared with structure length showed high variability in these data.

Cost Characteristics for Matching Bridges

As for timber bridges, the characteristics of valid matching steel, concrete, and prestressed concrete bridges were compared with those of the entire population of matching bridges to ensure that project data were broadly representative of the total population. Data from these comparisons are included in Appendix F. The comparisons revealed that the valid data set was generally representative of the total population for material type, construction type, width, number of lanes, load rating, and region.

Median cost for the timber data set was less than that for the steel data set and greater than that for the concrete and prestressed concrete data sets (Table 9). The middle 50% of observations was more tightly distributed for prestressed concrete than for the other materials (Fig. 3). Several outlying data points were observed for both timber and prestressed concrete bridges.

Table 9—Cost comparison of complete timber and nontimber valid data sets

Data set	Observations (no.)	Cost ($/ft^2)	
		Median	Mean
Timber	222	26.40	31.84
Steel	27	27.50	31.40
Concrete	37	19.13	27.53
Prestressed concrete	115	21.67	25.45
Total	401		

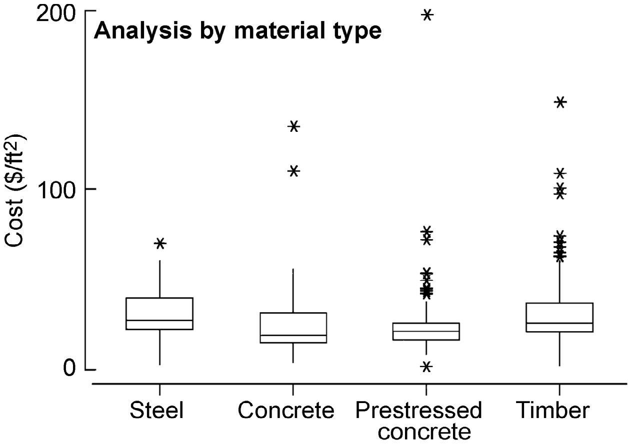


Figure 3—Percentage of timber bridges from valid data set and total population by construction type.

Cost Comparisons for Primary and Secondary Matching Schemes

Additional cost comparisons were conducted separately on two data sets of matched bridges. The primary set included costs from bridges matched on the basis of structure length, number of lanes, load rating, year constructed, and region. The secondary set, a subset of the primary, included costs from bridges that were further screened based on the tighter maximum span length criterion.

For data sets based on the primary matching scheme, the prestressed concrete set had the highest number of pairs (98), followed by steel (28) and concrete (20). Median and mean values are presented in Table 10.

The individual differences ($d_i = T_i - N_i$) were used to develop the box plot shown in Figure 4. Negative differences resulted when the cost per square foot for a given timber bridge was lower than the mean cost per square foot of the matched nontimber bridge. Accordingly, positive differences

Table 10—Cost comparison of primary and secondary data sets of matched timber and nontimber bridges

	Observations (no.)	Timber cost ($/ft^2)		Nontimber cost ($/ft^2)		Difference in cost ($d_i = T_i - N_i$)	
Data set		Median	Mean	Median	Mean	Median	Mean
Primary							
Steel	28	25.80	31.19	27.05	30.07	1.38	1.12
Concrete	20	28.65	27.90	23.49	35.22	3.01	–7.32
Prestressed concrete	98	24.51	28.29	21.57	24.37	3.05	3.92
Secondary							
Steel	16	26.90	32.81	34.88	33.78	–0.70	–0.96
Concrete	15	28.94	27.48	23.58	31.62	–0.55	–4.13
Prestressed concrete	45	24.66	27.37	17.21	21.34	4.94	6.03

resulted when the cost per square foot for a given timber bridge was greater than the mean cost per square foot of the matched nontimber bridge. In the resulting box plot, the median difference (m_d) was positive for each type of material. The middle 50% of observed differences was more closely distributed about the median difference for prestressed concrete than for steel or concrete.

For 46.4% of timber–steel matches, timber was less costly than steel. Similarly, for 45% of timber–concrete matches, timber was less costly than concrete. In contrast, timber was less costly than prestressed concrete for only 33.7% of timber–prestressed concrete matches.

The mean cost per square foot for steel, $30.07, was less than that for the matched timber set ($31.19) (Table 10). The mean cost per square foot for prestressed concrete, $24.37, was also lower than that for the matched timber set ($28.29). In contrast, the mean cost per square foot for concrete, $35.22, exceeded that for the matched timber set ($27.90).

The preceding analysis was applied to the secondary data set, bridges meeting the maximum span length criterion. Of the matched sets meeting this criterion, the prestressed concrete set was largest (45 observations), followed by steel (16) and concrete (15). The resulting median and mean values are summarized in Table 10.

As for the primary data set, individual differences ($d_i = T_i - N_i$) were used to develop the box plot for the secondary data set (Fig. 5). The median difference value (m_d) was positive for prestressed concrete and negative for steel and concrete. Again, the middle 50% of observed differences was more tightly distributed about the median for prestressed concrete than for steel or concrete.

For 50% of timber–steel matches, timber was less costly than steel. Timber was less costly than concrete for 53.3% of timber–concrete matches. Again, timber compared less favorably to prestressed concrete. Timber was less costly than prestressed concrete for only 24.4% of timber–prestressed concrete matches.

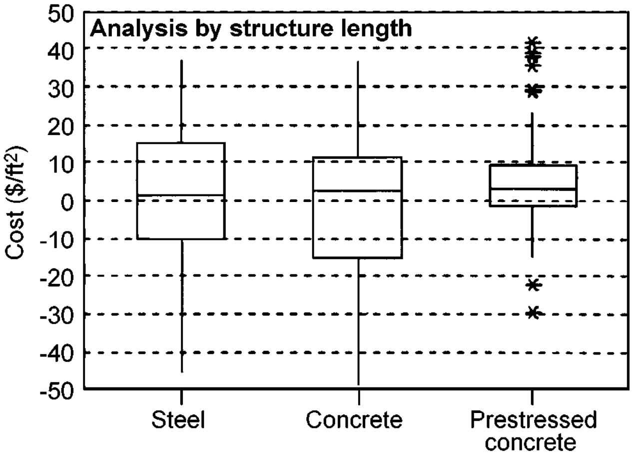


Figure 4—Percentage of timber bridges from valid data set and total population by structure length. Lower endpoint of each length interval is inclusive (closed); upper endpoint is noninclusive (open).

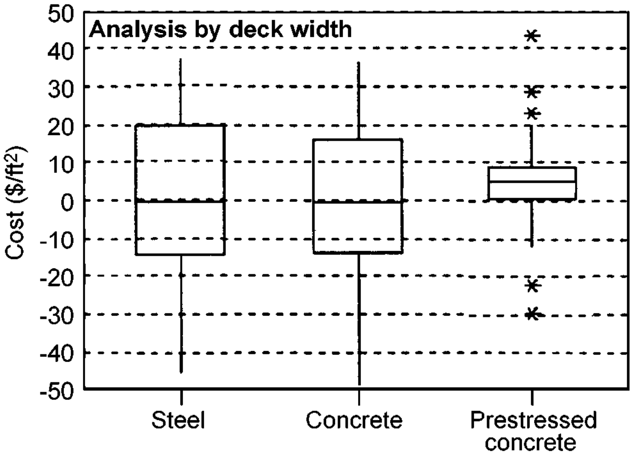


Figure 5—Percentage of timber bridges from valid data set and total population by deck width. Lower endpoint of each width interval is inclusive (closed); upper endpoint is noninclusive (open).

Mean cost per square foot for steel bridges ($33.78) and concrete bridges ($31.62) was higher than that for the matched timber sets ($32.81 and $27.48, respectively) (Table 10). Mean cost per square foot for prestressed concrete bridges ($21.34) was less than that for the matched timber set ($27.37).

Summary of Costs of Matched Bridges

Results of cost comparison analyses varied depending on the matching scheme adopted. The comparison of complete data sets by material type indicted that median cost per square foot was lowest for concrete bridges, followed by prestressed, timber, and steel bridges. The middle 50% of these data were more tightly distributed for prestressed concrete bridges when compared with bridges of other materials.

Results of comparisons based on primary and secondary matching schemes were as follows.

Primary matching scheme

- Median differences were positive for steel, concrete, and prestressed concrete bridges, indicating that the cost per square foot of timber bridges was greater than that of matched bridges at the median observation.
- Mean cost per square foot of timber bridges was greater than that of steel or prestressed concrete bridges and less than that of concrete bridges.

Secondary matching scheme

- Median differences were positive for concrete and prestressed concrete bridges and negative for steel bridges. That is, the cost per square foot of timber bridges was greater than that of concrete and prestressed concrete bridges and less than that of steel bridges at the median observation.
- Mean cost per square foot of timber bridges was less than that of steel or concrete bridges and greater than that of prestressed concrete.

In general, timber bridge superstructures tended to compete with steel and prestressed concrete bridge superstructures on an initial cost basis. Mean and median differences for each material were typically close to one another. More importantly, the ranges of cost per square foot for these bridges were highly variable and tended to overlap.

In contrast, cost per square foot values for prestressed concrete bridge superstructures tended to be more tightly distributed, with mean values consistently less than those for timber bridge superstructures. In addition, median differences for prestressed concrete were positive in both paired comparisons, suggesting that the cost per square foot of prestressed concrete bridge superstructures is less than that of timber bridge superstructures.

Cost Trends for Timber Bridges

The following text summarizes cost trends for timber bridges and provides possible explanations for data patterns. Possible causes for the variability in data are also discussed. Results are then summarized for the initial cost comparison of timber and nontimber bridges.

Timber Bridge Cost Characteristics

Results show a relationship between cost per square foot and bridge length, load rating, and geographic location. There appears to be a parabolic relationship between the cost per square foot of timber bridge superstructures and structure length, with higher costs for both the shortest and longest lengths. Cost per square foot also appears to increase with higher load rating. This result was expected because larger structural members are generally necessary to attain higher load ratings, other factors being constant (Ritter 1990). Finally, cost per square foot is higher for the Northeast region than for the Midwest. This observation is consistent with the findings of a 1994 Timber Bridge Information Resource Center report, in which average superstructure costs per square foot for the Wood in Transportation Program demonstration bridges were higher for the northeastern States of Pennsylvania and West Virginia than for all States in the Midwest and Northeast regions combined (USDA 1994).

The findings of the study reported here are limited by the wide variability in the available data and, in the case of load rating and region, by the limited number of data points for some categories. The high variability in the data may have been the result of unspecified cost factors, lack of standardization in timber bridge construction, or failure of some highway engineers to recognize the cost effectiveness of timber bridges.

It is likely that cost components not addressed in this study play an important role in determining bridge costs. For example, there may be location-specific cost determinants relating to material and equipment transportation. The lack of standardization in timber bridge design and construction, which has resulted in ad hoc assembly practices by various transportation agencies, may have also contributed to data variability. If so, the implementation of standardization efforts by Lee and others (1995) will likely lead to a reduction in timber bridge costs. Finally, it is clear from the range of cost data that many transportation officials have been able to achieve low cost per square foot values using timber bridges, perhaps because they are familiar with cost-effective timber bridge designs or experienced in timber bridge construction. In addition, timber bridges may have found their market niche in the form of small-crossing, rural, and, most important, nontraditional applications that encompass a wide-range of construction practices and design concepts unique to timber. The limited number of timber bridges greater than 100 ft in length and the lack of bridges of more than two lanes in width support this rationale.

Comparison of Timber and Nontimber Bridges

In general, the data indicate that timber bridge superstructures tend to compete with steel and prestressed concrete bridge superstructures on an initial cost basis. Mean and median costs for each type of material are typically close to one another. However, the range in cost per square foot values for all bridges varies widely. This outcome was likely due to both the high variability in the data and the relatively small sample size of the data sets for steel and prestressed concrete. Again, variability in the data may have stemmed from the absence of standardization in past timber bridge construction. If so, current efforts in standardization may serve to clarify the results of future cost comparisons, reduce timber bridge construction costs, and increase timber bridge construction.

In contrast, cost per square foot values for prestressed concrete bridge superstructures tend to be more tightly distributed, with mean values consistently lower than those for timber bridge superstructures. Median values for prestressed concrete bridges were positive in both paired comparisons, suggesting that prestressed concrete bridge superstructures cost less per square foot than do timber bridge superstructures. The higher cost of timber superstructures relative to that of prestressed concrete superstructures may be the result of underutilization of timber as a bridge material and subsequent lack of competition in the bridge market. Under this scenario, as more firms enter the timber bridge market, the cost of timber bridge superstructures should decrease, other factors remaining constant.

Future Research

As noted throughout this paper, the results of this study suggest a need for standardization in timber bridge construction and design. Only through such efforts will cost variability for timber bridges be minimized and knowledge about the true prospects for timber bridges be gained.

Work should also be directed toward a thorough comprehension of bridge cost components. Specifically, the determination of bridge costs should take into consideration the role of proximity to prestressing and pressure-treating facilities in urban areas. The effect of transportation costs (to and from such facilities) on bridge construction needs to be assessed. Such efforts might include multiple regression analysis of bridge cost determinants. The effect of construction method on bridge costs also needs to be evaluated.

The need for life-cycle cost analysis in timber bridge economics is widely recognized. Current data are prohibitively scarce; therefore, efforts should be directed towards more thorough recordkeeping at all government levels. Comparative studies need to match bridge materials. For example, timber slabs should be compared with prestressed concrete slabs and timber beams with steel beams. Finally, demonstration projects should be used to pave the way for research.

References

Behr, R.A.; Cundy, E.J; Goodspeed, C.H. 1990. Cost comparison of timber, steel, and prestressed concrete bridges. Journal of Structural Engineering. 116: 3448–3457.

Council of Economic Advisers. 1996. Economic report of the President. Washington, DC: U.S. Government Printing Office. (February) 402 p.

FHWA. 1988. Recording and coding guide for the structure inventory and appraisal of the nation’s bridges. Rep. FHWA–ED–89–044. Washington, DC: Federal Highway Administration. (December).

FHWA. 1994. National bridge inventory data as of June 1994. Washington, DC: Federal Highway Administration.

Hill, J.J.; Shirole, A.M. 1984. Economic and performance considerations for short-span bridge replacement structures. Transportation Resource Record. 950: 33–38.

Lee; P.D. Hilbrich; Ritter, M.A.; Triche, M. 1995. Standard plans for southern pine bridges. Gen. Tech. Rep. FPL–GTR–84. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

National Bureau of Standards. 1987. Codes for named populated place, primary county divisions, and other locational entities of the United States and outlying areas. FIPS PUB 55–2. 29 p.

Ritter, Michael A. 1990. Timber bridges: design, construction, inspection and maintenance. EM 770–8. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering Staff. 944 p.

Sarisley, E.F. 1990. Construction methods and costs of stress-laminated timber bridges. Journal of Construction Engineers and Management. 116: 432–447.

Smith, R.L.; R.J. Bush. 1994. Marketing practices in the timber bridge industry. Forest Products Journal. 44: 27–33.

USDA. 1993. Timber bridge initiative: superstructure costs report on project funded bridges 1989–1993. Morgantown, WV: U.S. Department of Agriculture, Forest Service, Northeastern Area, State and Private Forestry, Timber Bridge Information Resource Center.

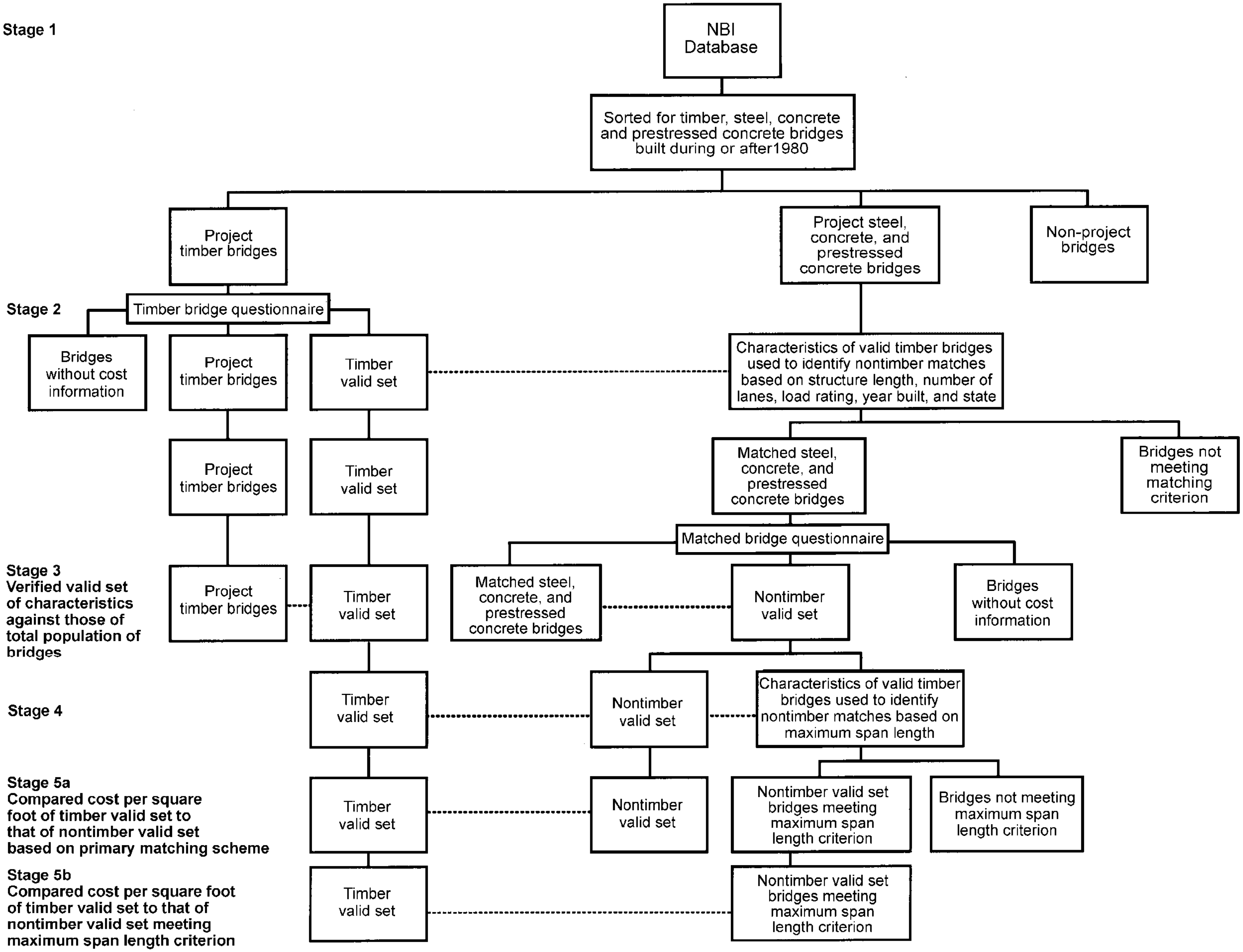
USDA. 1994. The timber bridge initiative, fiscal year 1994 status report. Radnor, PA: U.S. Department of Agriculture, Forest Service, State and Private Forestry, Northeastern Area. 14 p.

Verna, J.R.; Graham, J.F., Jr.; Shannon, J.M.; Sanders, P.H. 1984. Timber bridges: benefits and costs. Journal of Structural Engineering. 110: 1563–1571.

Wolchuk, R. 1988. The “first cost syndrome” in bridge rehabilitation. Civil Engineering. 58: 6.

Appendix A–Flowchart of Project Methodology

This flowchart outlines project research methodology in chronological order. Stage numbers are provided for cross referencing with the body of the report; they denote the major phases of project methodology.



Appendix B—Survey of Bridge Superstructure Cost

A questionnaire on bridge superstructure cost was sent to timber, steel, concrete, and prestressed concrete bridge owner–agencies throughout the United States.

The example of a demonstration project given in item 3 (Timber Bridge Initiative) was not included in the questionnaire given to the steel and concrete bridge owner–agencies. Otherwise, the questionnaires were identical.

Survey on the Cost of Timber Bridge Superstructures

Bridge Description/Type of Bridge:

Structure Number:

Feature Intersected:

Location:

County:

Year Built:

Structure Length (in feet):

1. Do the above characteristics accurately describe this bridge? If "no," please specify:

2. Please provide the following cost information for this bridge (Definitions of terms are listed below the table):

TOTAL SUPERSTRUCTURE COST (in dollars):	
TOTAL SUBSTRUCTURE COST (in dollars):	
TOTAL BRIDGE COST (in dollars):	

DEFINITIONS:

Superstructure cost - includes materials, labor, and transportation expenses associated with the construction of all bridge components **between abutments and above bents**. Includes stringers, beams, deck, traffic railing, wearing surface, and protective membrane. Please exclude approach, approach railing, detour, and mobilization costs.

Substructure cost - includes materials, labor, and transportation expenses associated with the construction of all bridge components **below the superstructure**. Includes abutments and bents. Please exclude approach, approach railing, detour, and mobilization costs.

Bridge cost - includes all materials, labor, and transportation expenses associated with the completion of the **entire** bridge project, with the exception of approach, approach railing, detour, and mobilization costs. Includes superstructure and substructure costs.

3. Was this bridge part of a federal, state, or other demonstration project (e. g. Timber Bridge Initiative)? If “yes,” please specify:

4. Describe any volunteer or donated labor, materials, or services used on this bridge that might affect how its cost would compare with those of similar bridges (e. g. prison labor, donated timber, other):

5. Who may we contact in the event that further information or clarification is required?:

Name:
Title:
Address:
City, State, Zip:
Phone:
Fax:

6. If available, please provide the following cost information:

Superstructure	**Cost (in dollars)**
Structure/Structural Members	
Deck	
Traffic Railing	
Wearing Surface	
Fabrication	
Erection	
Labor (if not previously included)	
Miscellaneous	
TOTAL:	

7. If available, please include a copy of the final project cost worksheet.

8. How many companies placed a bid for the project in question?: ______________________________

9. If available, please provide the following contractor/supplier information:

Primary contractor for bridge superstructure:

Firm: ______________________________

Contact: ______________________________

Address: ______________________________

City, State, Zip: ______________________________

Phone: ______________________________

Fax: ______________________________

Primary supplier of superstructure materials (if different from contractor):

Firm: ______________________________

Contact: ______________________________

Address: ______________________________

City, State, Zip: ______________________________

Phone: ______________________________

Fax: ______________________________

Please return this form to:

Glade Michael Sowards
Michigan Technological University
School of Forestry and Wood Products
1400 Townsend Dr.
Houghton, MI 49931-1295

Phone: **(906) 487-3598**
Fax: **(906) 487-2915**

Appendix C—Complete Data Set

The table in Appendix C shows NBI data and cost per square foot values for the timber bridge valid data obtained from owner–agencies. Cost per square foot values for steel, concrete, and prestressed concrete matched bridges are also provided.

									Adjusted cost ($\$/ft^2$)			
NBI struct. no.[a]	Construction type	Struct. length (ft)	Max. span length (ft)	Deck width (ft)	No. of lanes	Load rating	Year built	State	Timber	Steel	Con-crete	Pre-stressed-concrete
012507	Stringer/multi-beam or girder	40	24	16	2	H10	1981	AL	4.79			
014472	Stringer/multi-beam or girder	72	72	20	1	H15	1988	AL	2.99			
014474	Stringer/multi-beam or girder	30	30	16	1	H15	1988	AL	3.59			
PUCO0.01-204BR	Stringer/multi-beam or girder	32	31	30	2	HS20	1990	CO	31.68		39.46	
USFS15310-0.1	Stringer/multi-beam or girder	84	39	15	1	HS20	1985	CO	36.98			
067024300.6010A	Girder & floorbeam system	58	54	32.3	2	HS20	1992	CO	45.25			25.15
000000000103121	Stringer/multi-beam or girder	29	27	24	2	H20	1990	IA	31.33			
000000000142511	Stringer/multi-beam or girder	60	20	22	2	H15	1981	IA	8.28			
000000000183441	Stringer/multi-beam or girder	56	28	25	2	H15	1985	IA	6.99			
000000000213282	Stringer/multi-beam or girder	22	21	24	2	H15	1992	IA	7.94			
000000000214381	Stringer/multi-beam or girder	65	22	24	2	H20	1986	IA	4.90			
000000000217459	Stringer/multi-beam or girder	84	32	30	2	H20	1984	IA	19.06			24.01
000000000245851	Other	32	32	24	2	HS20	1990	IA	13.14	7.61	27.32	
000000000305411	Stringer/multi-beam or girder	33	33	25.6	2	HS20	1990	IA	44.94	7.61		
000000000324401	Stringer/multi-beam or girder	80	39	24	2	HS20	1992	IA	21.56			
000000000324631	Other	26	25	24.5	2	HS20	1990	IA	17.44			
000000000324650	Stringer/multi-beam or girder	39	20	23.2	2	H20	1990	IA	17.68	2.70		
000000000325201	Other	52	25	22	2	HS20	1989	IA	18.17			20.65
000000000325711	Other	40	40	24.8	2	HS20	1988	IA	17.37			18.62
000000000326871	Other	40	20	23	2	HS20	1992	IA	15.80			
000089326229675	Stringer/multi-beam or girder	120	32	26	2	HS20	1992	IL	28.02		26.82	
0200030	Stringer/multi-beam or girder	201	40	32.1	2	HS20	1982	IN	27.28			16.65
3200002	Slab	24	22	27.5	2	HS20	1988	IN	56.30			18.32
3200112	Slab	26	24	27.5	2	HS20	1988	IN	63.41			21.76
3200219	Slab	26	24	25.5	2	HS20	1987	IN	57.57			21.76
3200220	Slab	26	24	25.6	2	HS20	1987	IN	60.91			21.76
6000139	Stringer/multi-beam or girder	52	24	21.5	2	HS20	1985	IN	30.90		19.13	
8000004	Slab	32	30	32.3	2	HS20	1980	IN	34.05			
9000032	Slab	78	25	26	2	HS20+Mod	1980	IN	32.41			
9000042	Slab	54	26	25.5	2	HS20	1986	IN	26.87		19.13	
TWN719045100	Stringer/multi-beam or girder	59	20	24.8	2	H20	1986	MA	25.11			
200000D-0018010	Slab	36	36	28	2	HS20	1992	MD	36.47			
0332	Other	35	27	44	2	HS20	1992	ME	48.73			
10307H00020B010	Slab	44	22	30	2	HS20	1987	MI	24.84			25.25
26306H00002B010	Slab	24	22	18	2	HS20+Mod	1983	MI	101.33			34.94
34315H00005B010	Slab	72	24	32	2	HS20+Mod	1989	MI	34.21			26.54
34315H00023B010	Slab	66	30	32	2	HS20+Mod	1985	MI	21.06			
37302H00002B020	Slab	30	28	20.3	2	HS20	1983	MI	38.34	22.77		
37302H00003B080	Stringer/multi-beam or girder	24	22	31.5	2	HS20	1980	MI	35.58			
41322H34031B010	Truss,thru	114	103	14	0	HS20+Mod	1980	MI	63.27			
42142021000B050	Arch,deck	152	152	40	2	HS25	1988	MI	39.09			

									Adjusted cost ($/ft^2)			
NBI struct. no.[a]	Construction type	Struct. length (ft)	Max. span length (ft)	Deck width (ft)	No. of lanes	Load rating	Year built	State	Timber	Steel	Con-crete	Pre-stressed concrete
43200042000B070	Slab	72	24	35	2	HS20+Mod	1987	MI	26.74			26.54
43200050000B020	Slab	55	24	32	2	HS20	1991	MI	33.68			
44304H00009B010	Slab	52	26	28	2	H10	1991	MI	31.44			
44308H00020B010	Slab	24	22	29.8	2	HS20+Mod	1985	MI	3.54			33.16
44314H00020B010	Slab	128	32	34	2	HS20+Mod	1988	MI	26.64			22.12
44316H00004B020	Slab	26	25	27.3	2	HS20+Mod	1984	MI	2.84		51.47	25.03
49149022000B050	Slab	26	26	24	2	HS20	1990	MI	30.76		46.54	
58304A00021B020	Slab	26	24	29.3	2	HS20+Mod	1990	MI	29.98		51.47	27.31
59309H00030B010	Other	27	26	22.5	2	HS20+Mod	1989	MI	28.94		40.54	25.03
59310H00021B010	Other	24	24	23.5	2	HS20+Mod	1989	MI	58.21			29.59
67310H00003B010	Slab	52	25	36	2	HS20+Mod	1985	MI	74.68			23.13
67316H00001B010	Other	242	61	29	2	HS20+Mod	1982	MI	71.25			
74307H00002B010	Slab	52	24	34	2	HS20	1991	MI	37.16			198.33
74307H00005B010	Slab	54	26	34	2	HS20	1991	MI	35.78			
77312H00012B010	Slab	36	35	36	2	HS20+Mod	1991	MI	37.21		110.65	
81307H00037B010	Slab	44	21	32.9	2	HS20+Mod	1980	MI	35.56			
81307H00040B010	Slab	70	26	30	2	HS20+Mod	1984	MI	26.15			26.96
81319H00027B010	Slab	72	24	32	2	HS20+Mod	1989	MI	26.12			26.54
83307H00010B010	Slab	22	22	30	2	HS20	1990	MI	46.85			
01513	Slab	96	32	34	2	HS20	1980	MN	22.61			
02534	Slab	72	24	34	2	HS20	1986	MN	22.95			21.90
02535	Slab	60	20	46	2	HS20	1984	MN	22.39			19.29
02554	Slab	62	22	34.6	2	HS20	1991	MN	35.77			21.09
11514	Slab	62	26	34	2	HS20	1988	MN	17.48			17.99
15509	Slab	90	30	34	2	HS20	1982	MN	16.71			21.94
17524	Slab	96	32	30	2	HS20	1983	MN	23.64			
17526	Slab	84	32	30	2	HS20	1985	MN	17.61			23.14
17527	Slab	116	32	30	2	HS20	1986	MN	16.85		12.04	18.77
18511	Slab	60	24	32	2	HS20	1986	MN	20.06			17.99
18512	Slab	93	30	37.3	2	HS20	1984	MN	20.05			21.94
18513	Slab	93	30	34	2	HS25	1991	MN	25.22		19.24	
18514	Slab	78	26	34	2	HS20	1981	MN	4.94			19.99
18519	Slab	62	26	26.3	2	HS20	1990	MN	18.07			21.09
22552	Slab	95	31	30	2	HS20	1980	MN	32.34			27.58
22555	Slab	62	26	30	2	HS20	1980	MN	25.42			14.89
22557	Slab	72	24	30	2	HS20	1981	MN	24.18			20.67
22562	Slab	96	32	30	2	HS20	1982	MN	25.70			
22564	Slab	78	26	30	2	HS20	1985	MN	24.27			15.13
22566	Slab	77	25	30	2	HS20	1984	MN	24.36			16.84
22567	Slab	62	26	30	2	HS20	1982	MN	23.10			16.35
22569	Slab	84	32	30	2	HS20	1984	MN	22.77			
22570	Slab	70	26	30	2	HS20	1986	MN	21.94			22.51
22571	Slab	84	32	30	2	HS20	1987	MN	22.93			
22573	Slab	89	29	30	2	HS20	1988	MN	28.12			
22574	Slab	72	24	30	2	HS20	1985	MN	25.78			21.90
22575	Slab	89	29	30	2	HS20	1985	MN	29.00			16.31

									Adjusted cost ($/ft^2)			
NBI struct. no.[a]	Construction type	Struct. length (ft)	Max. span length (ft)	Deck width (ft)	No. of lanes	Load rating	Year built	State	Timber	Steel	Con-crete	Pre-stressed concrete
25530	Slab	62	26	34	2	HS20	1986	MN	15.53			17.99
29512	Slab	72	24	34	2	HS20	1981	MN	17.55			20.67
29516	Slab	38	36	30	2	HS20	1986	MN	37.37			
29518	Slab	38	36	34	2	HS20	1991	MN	43.58			
32535	Slab	67	31	38.3	2	HS20	1986	MN	24.62			
33516	Slab	77	25	38.3	2	HS20	1986	MN	17.73			16.84
33521	Slab	124	32	38.2	2	HS20	1981	MN	23.65	22.21	12.04	21.38
33523	Slab	86	28	30	2	HS20	1985	MN	24.40			
33524	Slab	62	26	30	2	HS20	1989	MN	18.76			19.25
33526	Slab	94	31	30	2	HS20	1987	MN	24.73			
36518	Slab	103	34	26	2	HS20	1986	MN	23.87			16.27
37530	Slab	95	31	30	2	HS20	1982	MN	23.14			
39509	Stringer/multi-beam or girder	102	34	30	2	HS20	1986	MN	25.07			16.56
39516	Slab	78	26	30	2	HS20	1990	MN	23.58			15.97
42530	Slab	96	32	30	2	HS20	1980	MN	22.60			22.07
42534	Slab	90	30	30	2	HS20	1980	MN	22.57			21.94
45533	Slab	132	32	26	2	HS20	1980	MN	26.00	22.21		15.57
47522	Slab	78	26	34	2	HS20	1980	MN	9.44			15.15
47523	Slab	78	26	30	2	HS20	1981	MN	34.51			16.84
47524	Slab	160	32	38.2	2	HS20	1985	MN	29.19			
47526	Slab	160	32	34	2	HS20	1980	MN	38.83	19.29		
47529	Slab	96	32	30	2	HS20	1984	MN	44.62			
47530	Slab	65	21	34	2	HS20	1984	MN	43.15			22.89
49527	Slab	108	28	30	2	HS20	1981	MN	24.66	27.05		20.02
49531	Slab	128	32	34	2	HS20	1986	MN	18.38			22.65
49532	Slab	112	37	34	2	HS20	1989	MN	28.37	27.05	12.04	20.96
49533	Slab	90	30	34	2	HS20	1989	MN	19.51			
49534	Stringer/multi-beam or girder	150	50	34	2	HS20	1985	MN	25.00	21.76		20.17
49536	Slab	94	31	30	2	HS20	1990	MN	29.50			
49537	Slab	88	32	38	2	HS20	1991	MN	23.94			
52509	Stringer/multi-beam or girder	49	48	34	2	HS20	1986	MN	24.30			
52510	Slab	96	32	30	2	HS20	1990	MN	29.59			
53530	Slab	95	31	34	2	HS20	1986	MN	24.12			
56527	Slab	58	22	34.6	2	HS20	1987	MN	36.58			19.29
56528	Slab	78	26	42	2	HS20	1987	MN	16.15			15.13
59516	Slab	104	26	30	2	HS20	1987	MN	15.92	27.05		17.74
59520	Slab	68	32	30	2	HS20	1991	MN	21.77			22.97
64538	Slab	90	30	30	2	HS20	1980	MN	26.14			21.94
64539	Slab	104	26	30	2	HS20	1982	MN	19.56	27.05		16.27
64540	Slab	90	30	30	2	HS20	1982	MN	22.05			21.94
64544	Slab	144	36	30	2	HS20	1989	MN	27.13			17.21
64546	Slab	78	26	30	2	HS20	1988	MN	20.07			15.13
64547	Slab	68	32	30	2	HS20	1990	MN	23.85			22.97
72529	Slab	96	32	38	2	HS20	1987	MN	19.86			
74533	Slab	78	26	32	2	HS20	1987	MN	20.64			15.13
77514	Slab	62	26	28	2	HS20	1983	MN	19.30			17.99

									Adjusted cost (\$/ft^{2})			
NBI struct. no.[a]	Construction type	Struct. length (ft)	Max. span length (ft)	Deck width (ft)	No. of lanes	Load rating	Year built	State	Timber	Steel	Con- crete	Pre- stressed concrete
77515	Slab	66	30	46	2	HS20	1980	MN	21.59			
77516	Slab	32	30	34	2	HS20	1980	MN	23.65			
77519	Slab	76	25	34	2	HS20	1983	MN	20.86			20.67
80518	Slab	128	32	30	2	HS20	1984	MN	19.38	22.21		22.61
80521	Slab	78	26	30	2	HS20	1990	MN	17.54			15.97
80522	Slab	79	31	30	2	HS20	1988	MN	18.97			15.13
81524	Slab	92	32	34	2	HS20	1991	MN	20.62			
83519	Slab	96	32	30	2	HS20	1981	MN	21.53			22.07
83520	Slab	95	31	30	2	HS20	1981	MN	21.77			21.94
83522	Slab	90	30	30	2	HS20	1987	MN	25.53			16.31
83523	Slab	120	30	31	2	HS20	1990	MN	19.66		12.04	14.99
83529	Slab	128	32	30	2	HS20	1988	MN	22.08			19.08
999901003600450	Frame	21	21	20	1	H10	1990	MS	149.50			
999915663400060	Stringer/multi-beam or girder	67	20	24	2	H10	1991	MS	23.91			
000000009121320	Other	88	31	30.3	2	HS20+Mod	1985	ND	21.30			
000000009133260	Stringer/multi-beam or girder	52	50	34.7	2	HS20	1991	ND	36.28			
C004000303	Stringer/multi-beam or girder	61	30	20.1	2	H15	1986	NE	7.87			
03E4900	Boxbeam or girders,multiple	45	21	29.1	2	HS20+Mod	1987	NJ	34.77		135.73	
10XXT82	Stringer/multi-beam or girder	55	51	27.6	2	HS20+Mod	1986	NJ	43.02			45.20
10XXT83	Stringer/multi-beam or girder	54	49	27.3	2	HS20+Mod	1989	NJ	35.73			45.20
1000A65	Slab	36	34	37.3	2	HS20	1981	NJ	55.91			
1000L61	Slab	29	27	25.8	2	HS20+Mod	1983	NJ	30.55			
1000095	Slab	25	23	27.3	2	HS20	1990	NJ	55.68			
1000124	Slab	30	27	27.7	2	HS20+Mod	1985	NJ	26.96			33.02
1507020	Stringer/multi-beam or girder	101	25	35.5	2	HS20+Mod	1988	NJ	41.22			28.19
1516003	Boxbeam or girders,multiple	104	26	29	2	HS20	1985	NJ	31.93			
1516004	Boxbeam or girders,multiple	200	48	29	2	HS20	1985	NJ	38.33			
1518014	Other	57	28	25	2	HS20	1980	NJ	34.74			
1530002	Other	28	25	31.3	2	HS20	1980	NJ	34.66			
1530003	Other	23	20	31.3	2	HS20	1980	NJ	36.75			
000000002208110	Stringer/multi-beam or girder	72	34	27.1	2	HS20	1991	NY	47.62			44.09
000000002216750	Stringer/multi-beam or girder	30	27	26	2	HS20	1992	NY	27.80	39.81		
000000002218030	Slab	34	33	24.2	2	HS20	1992	NY	31.94			
000000002218630	Stringer/multi-beam or girder	48	46	25.1	2	Other	1986	NY	45.33			
000000003217560	Slab	24	23	29.4	2	Other	1986	NY	22.94			
000000003219250	Slab	82	30	32.2	2	HS20+Mod	1991	NY	38.74			
000000003219420	Stringer/multi-beam or girder	47	46	23.1	2	Other	1985	NY	59.38			
000000003307940	Stringer/multi-beam or girder	66	61	26	2	HS20	1992	NY	35.24			50.08
000000003317930	Stringer/multi-beam or girder	60	59	20.5	2	HS15	1989	NY	46.92			
000000003332810	Slab	32	31	32.3	2	HS20	1990	NY	24.48	54.88		
000000003332950	Slab	29	28	30.4	2	HS20	1990	NY	25.60	39.81		
000000003333090	Slab	31	29	30.1	2	Other	1990	NY	25.75			
000000003333140	Slab	32	31	32.1	2	HS20	1988	NY	24.17	69.65		
000000003333210	Slab	30	28	32.1	2	HS20	1988	NY	25.22	39.81		
000000003333540	Slab	28	27	30.1	2	HS20	1991	NY	25.22			

NBI struct. no.[a]	Construction type	Struct. length (ft)	Max. span length (ft)	Deck width (ft)	No. of lanes	Load rating	Year built	State	Adjusted cost ($/ft^2)			
									Timber	Steel	Con-crete	Pre-stressed concrete
000000003333680	Stringer/multi-beam or girder	50	49	33	2	HS20	1991	NY	44.00			20.91
000000003333770	Stringer/multi-beam or girder	30	28	32.3	2	HS20	1991	NY	34.90	39.81		
000000003333910	Slab	30	29	30.2	2	Other	1991	NY	24.81			
000000003334220	Slab	28	25	30.2	2	Other	1990	NY	25.57			
000000003334450	Slab	36	34	32.2	2	Other	1989	NY	28.14			
000000003334900	Stringer/multi-beam or girder	39	37	26.1	2	HS20	1991	NY	28.22	55.47		36.28
000000003334940	Stringer/multi-beam or girder	48	46	25.9	2	HS20	1990	NY	29.83			15.32
000000003357610	Slab	23	20	29	2	HS20+Mod	1982	NY	51.65			
000000003359330	Slab	36	35	35	2	HS20	1985	NY	44.83			
0433780	Truss,thru	104	98	18.7	1	HS20	1986	OH	57.08			
4438507	Slab	30	28	22	2	HS20	1990	OH	42.38	22.81	5.81	29.23
4458567	Stringer/multi-beam or girder	25	24	15	1	HS20	1991	OH	4.71			
6603165	Stringer/multi-beam or girder	128	31	30.2	2	HS20	1981	OH	19.55	27.62		19.23
7630786	Stringer/multi-beam or girder	29	29	29.2	2	HS20+Mod	1980	OH	49.15	39.83		20.02
8131422	Slab	62	26	26.3	2	HS20	1982	OH	20.68	27.50		
1419926200120	Stringer/multi-beam or girder	25	23	31	2	H20	1988	OR	28.76			
167213052600240	Stringer/multi-beam or girder	44	43	24	2	HS20+Mod	1991	PA	98.01			
327220040600560	Stringer/multi-beam or girder	57	54	26.1	1	HS20+Mod	1991	PA	52.39			
647205033200040	Stringer/multi-beam or girder	38	35	18.8	2	H20	1985	PA	34.85			42.71
000000041095085	Boxbeam or girders,singleorspread	65	63	38	2	HS20+Mod	1992	SD	51.69			
017042A	Slab	23	20	16.1	1	HS20	1987	UT	46.58			
079963000000000	Stringer/multi-beam or girder	82	77	27.4	2	HS20	1983	WA	32.08			21.86
080131000000000	Stringer/multi-beam or girder	35	33	18.1	2	H20	1984	WA	20.03			
084354000000000	Stringer/multi-beam or girder	88	20	20	2	H20	1985	WA	13.29			
084429000000000	Stringer/multi-beam or girder	47	45	29.5	2	HS20	1983	WA	25.84			22.26
085636000000000	Stringer/multi-beam or girder	58	58	28.9	2	HS25	1989	WA	49.18			
085890000000000	Stringer/multi-beam or girder	60	57	32	2	HS20	1992	WA	41.25		23.40	
B14007900000000	Stringer/multi-beam or girder	37	35	32	2	HS20+Mod	1980	WI	41.50			
B36012000000000	Slab	25	23	30	2	HS20+Mod	1982	WI	63.53			
P13010300000000	Stringer/multi-beam or girder	43	39	32	2	HS20+Mod	1992	WI	50.09		23.58	42.78
P36008700000000	Slab	84	32	29.5	2	HS20+Mod	1981	WI	15.00			
P36016000000000	Slab	67	32	29	2	HS20+Mod	1982	WI	15.44		15.99	
P71006000000000	Slab	26	25	31.3	2	HS20+Mod	1984	WI	35.22			
00000000006A045	Stringer/multi-beam or girder	65	63	23.8	2	HS20	1992	WV	46.44	36.51		
00000000015A015	Boxbeam or girders,multiple	43	40	17.6	1	HS20	1990	WV	109.54			
00000000018A027	Boxbeam or girders,multiple	44	40	22.1	2	H15	1990	WV	65.60			
00000000020A126	Stringer/multi-beam or girder	75	72	17.3	1	HS20	1988	WV	61.07	39.96		
00000000027A035	Teebeam	43	40	18.1	2	HS20	1990	WV	71.09			
00000000027A036	Boxbeam or girders,multiple	44	40	18.1	2	HS20	1991	WV	68.58			
00000000030A044	Stringer/multi-beam or girder	52	50	14.8	1	HS20	1990	WV	49.54			
00000000043A027	Boxbeam or girders,multiple	40	37	18.3	1	HS20	1990	WV	56.02	29.95		
00000000044A100	Teebeam	54	49	23.8	2	HS20	1992	WV	57.11			
00000000051A074	Slab	44	21	25.8	2	HS20	1988	WV	27.92			
00000000052A048	Slab	25	21	19.6	1	HS20	1990	WV	52.11	21.98		

Appendix D—Verification of Valid Data Set for Timber Bridges

To verify the validity of the data set, timber bridge data were compared with data from the total bridge population by construction type, structure length, structure width, number of lanes, load rating, year constructed, and region (Figs. 6 to 12). Responses were received for 556 of the original 1,604 timber bridges surveyed; 223 of these responses included complete cost information.

Information on construction type was available for 1,554 bridges; 209 of these bridges were considered valid. Together, slab and stringer/multi-beam bridges constituted more than 90% of the valid data set and the total population of timber bridges. Slab and box beam or girder bridges were overrepresented in the valid data set, and stringer/multi-beam bridges were underrepresented (Fig. 6). Other construction types constituted only a small fraction of the total population.

Complete information on out-to-out structure length was provided for 1,591 bridges; of these, 223 bridges were considered valid. The percentage of bridges from the valid data set appeared to be about proportional to the percentage of bridges from the total population for each 10-ft interval (Fig. 7). The greatest discrepancy was the smaller percentage of valid bridges between 20 and 30 ft long compared with the percentage of bridges in that range from the total population. Bridges in this category made up nearly 30% of the total population, and less than 15% of the bridges in the valid data set fell into the same range. The underrepresentation of bridges shorter than 30 ft may stem from a lack of reliable recordkeeping for short, relatively inexpensive timber bridges. Questionnaire comments support this assumption, as do the trends in other bridge characteristics.

Of the initial 1,604 timber bridges, complete information on width was provided for 1,570 bridges. All 223 bridges of the valid data set had usable information on width. Bridges ranged between 10 and 65 ft wide, although more than 90% were between 15 and 35 ft wide. Narrower bridges tended to be underrepresented in the valid data set. Bridges between 10 and 30 ft wide were a smaller percentage of the valid data set compared with the total population of bridges (Fig. 8). Again, this may be the result of a deficiency in recordkeeping for smaller, less-sophisticated bridges. In contrast, wider bridges tended to be overrepresented. It is reasonable to assume that larger projects with higher total costs are better documented and that data for such projects are more readily available.

Information on the number of lanes that cross each bridge was provided for 1,571 bridges; 222 bridges were considered valid. Only one- and two-lane bridges were present in the total population. The lane characteristics of the valid bridges appeared to follow those of the total population (Fig. 9). Any discrepancies followed the general trend described for bridge length and width, with an underrepresentation of the smaller, single-lane bridges and a slightly higher percentage of the larger, two-lane bridges in the valid data set.

Information on load rating was missing for several bridges in the total population. Only 1,517 bridges were valid in regard to this characteristic. Seven load ratings were represented in the total data set: H10, H15, HS15, H20, HS20, HS20+Mod, and HS25. More than 85% of the total population was represented by H10, HS20, and HS20+Mod bridges. HS20 bridges accounted for 58.7% of the total population. The trend towards underrepresentation of smaller bridges in the valid data set was as apparent for load rating as for other characteristics (Fig. 10). Only 1.9% of the valid data set consisted of H10 load-rated bridges, compared with 12.9% of the total population. The H15, HS15, and H20 categories were all slightly underrepresented in the valid data set. Conversely, HS20 and HS20+Mod bridges were overrepresented in the valid data set; HS25 bridges were almost evenly represented in the data sets.

Information on year of construction was provided for 1,590 bridges; of these, 222 bridges were valid. Bridge construction was underrepresented between 1981 and 1984, and overrepresented between 1990 and 1992 (Fig. 11). However, there was no identifiable trend between the valid data set and the total population associated with year of construction. No discrepancy was greater than 4%.

The initial population of 1,604 timber bridges was spread across the country among 47 States. Regional boundaries were adopted from a USDA Timber Bridge Information Resource Center (TBIRC) report (USDA 1993). For clarity, the Northeastern TBIRC region was split into two new regions: Midwest and Northeast. Within the valid data set, the two largest regions were the Northeast (54 data points) and the Midwest (148 data points) (Fig. 12). No cost information was received from the Alaska, California, and Southwest regions. The remaining regions each had between one and seven valid bridges within their boundaries. The Intermountain and Southeast regions were underrepresented in the valid data set. Although valid data set shortfalls for most regions represented an actual difference of only one or two bridges, valid data set underrepresentation for the Southeast, a region that accounts for 18.4% of the total population set, represented an actual difference of 35 fewer bridges than expected. Finally, there was a slightly higher percentage of valid data set responses for the Midwest and Northeast regions.

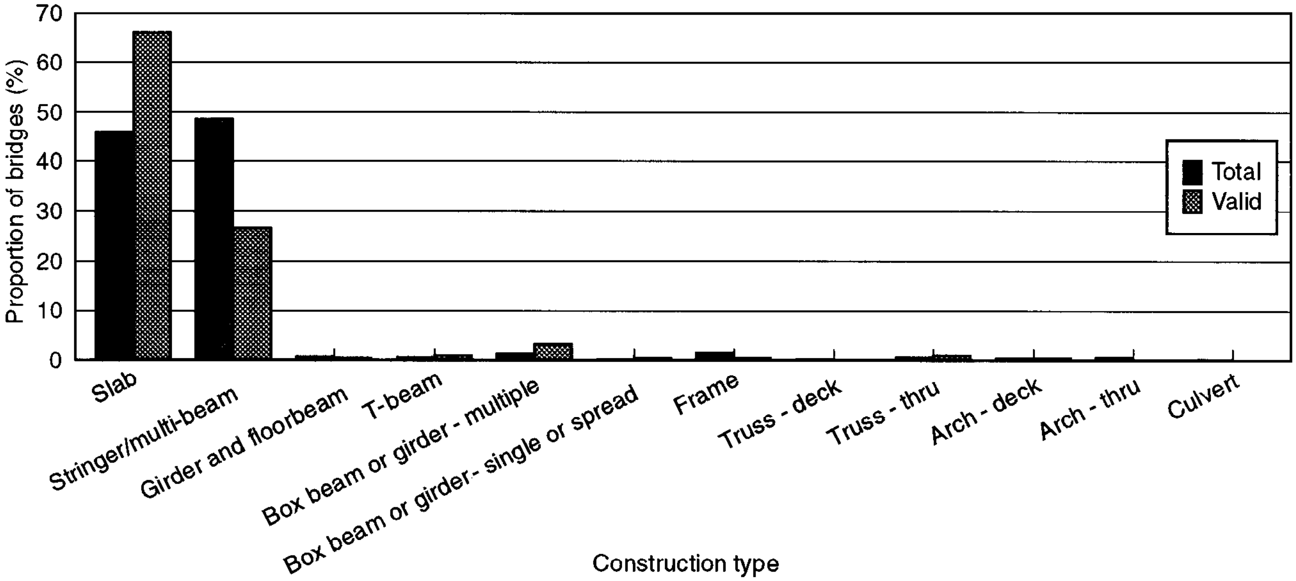


Figure 6—Percentage of timber bridges from valid data set and total population by construction type.

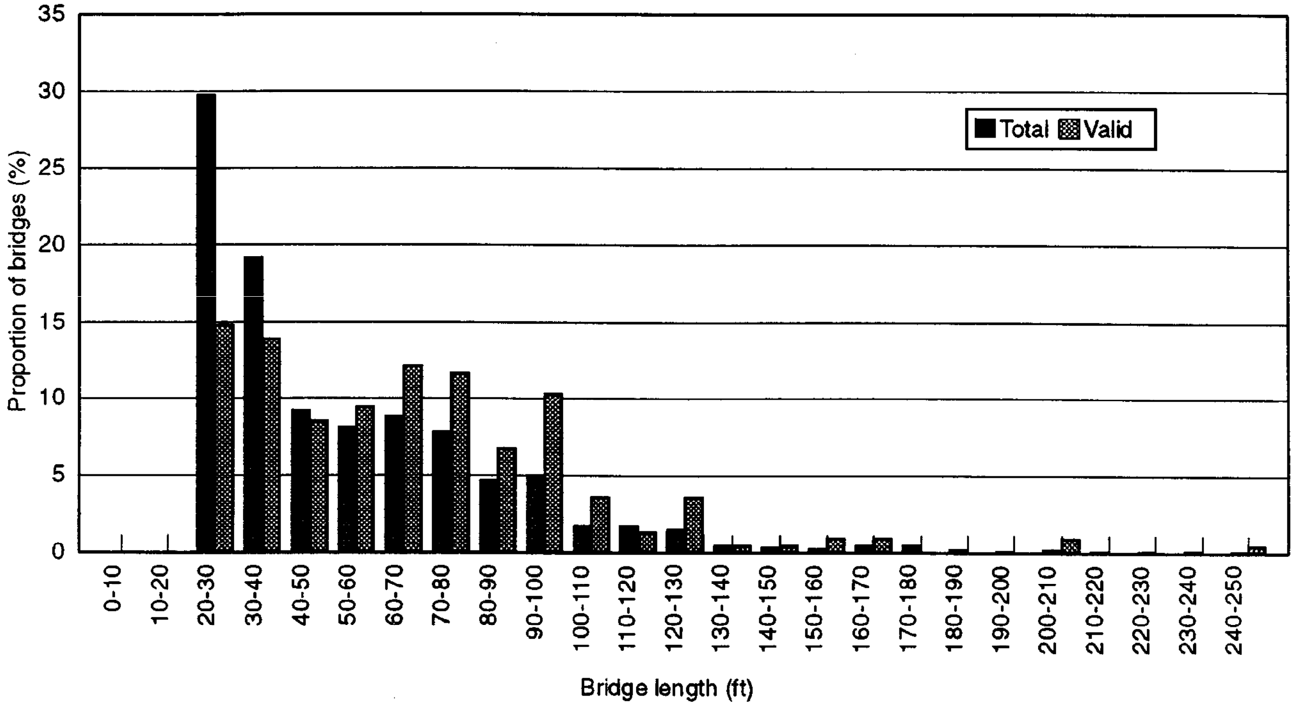


Figure 7—Percentage of timber bridges from the valid data set and total population by structure length. The lower endpoint of each length interval is inclusive (closed). The upper endpoint of each length interval is non-inclusive (open).

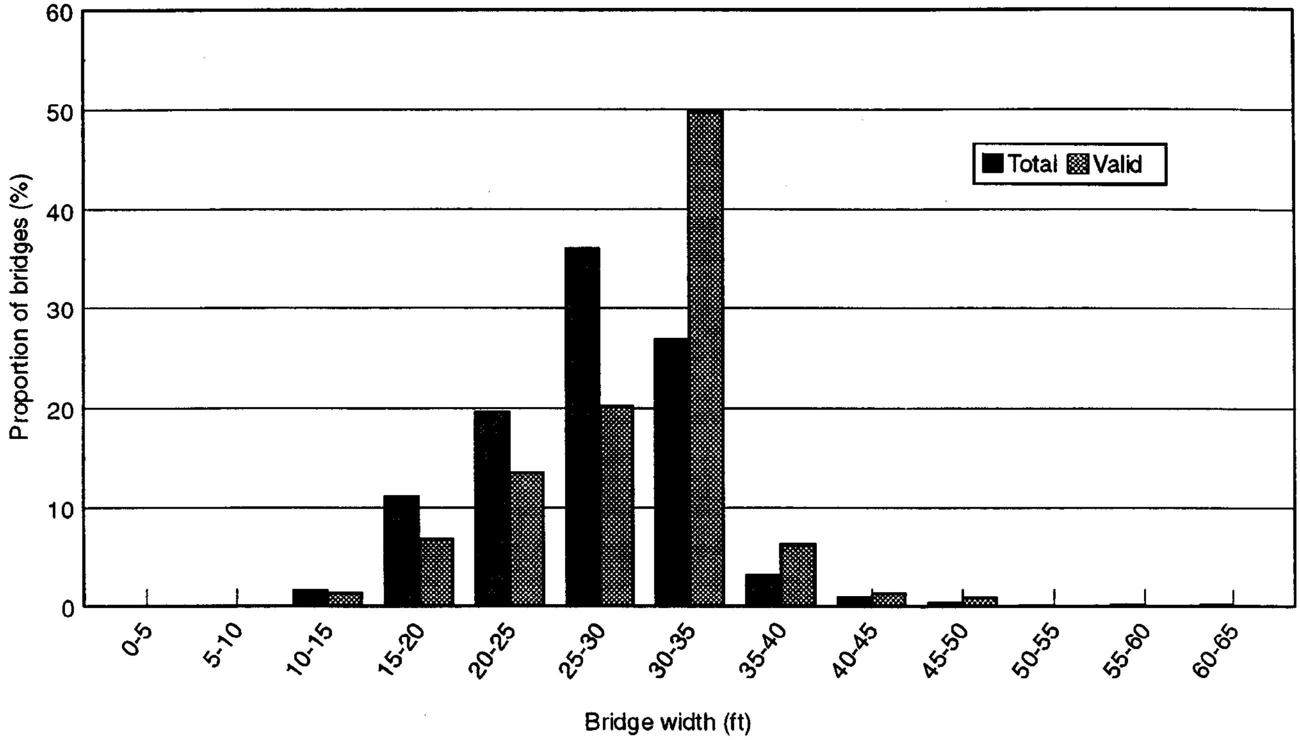


Figure 8—Percentage of timber bridges from the valid data set and total population by width. The lower endpoint of each length interval is inclusive (closed). The upper endpoint of each length interval is non-inclusive (open).

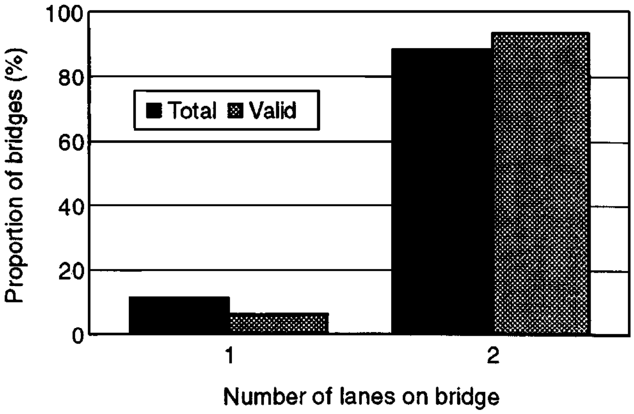


Figure 9—Percentage of timber bridges from the valid data set and total population by number of lanes.

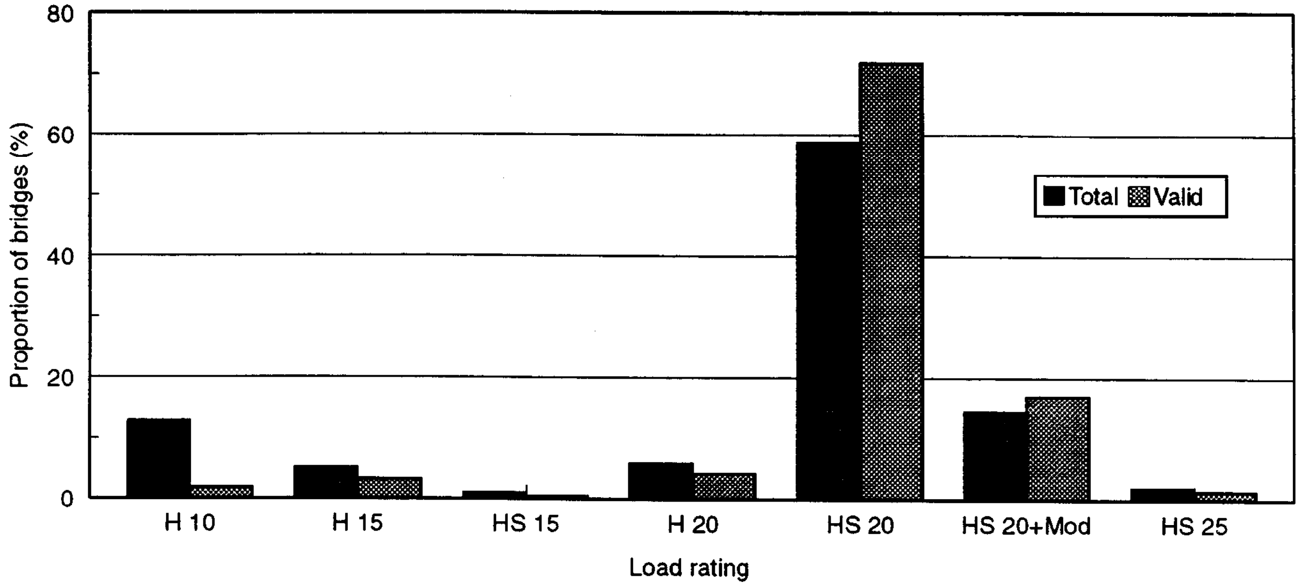


Figure 10—Percentage of timber bridges from the valid set and total population by load rating.

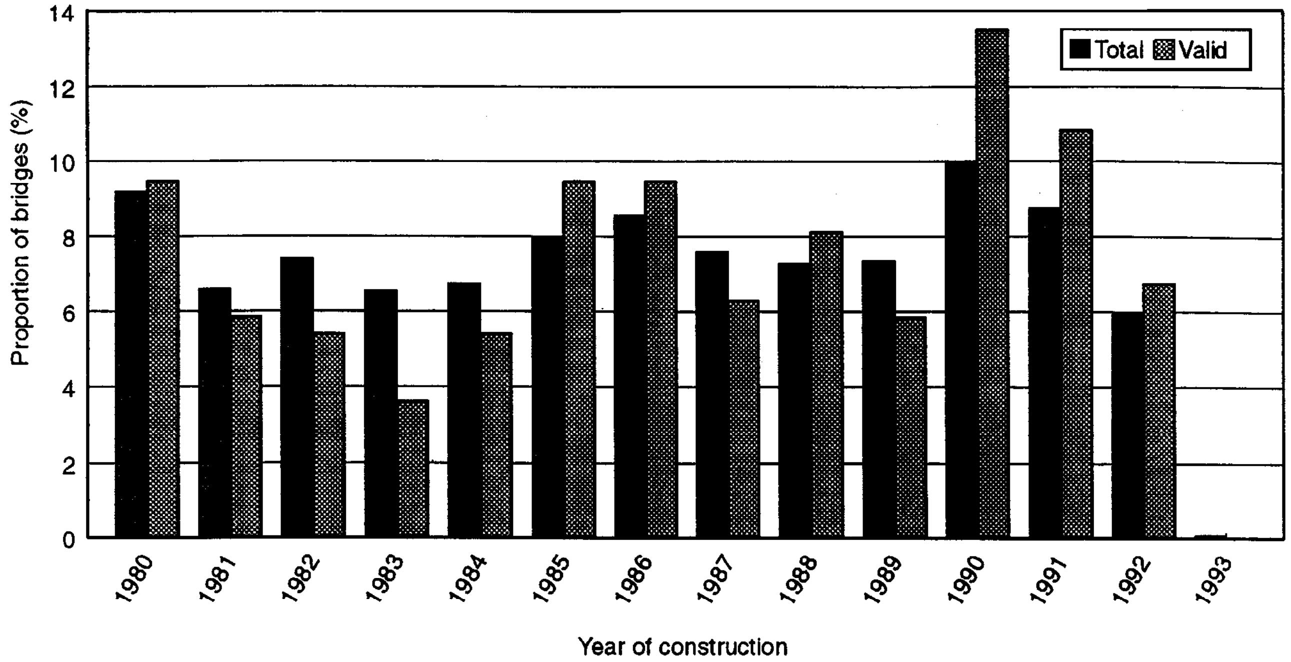


Figure 11—Percentage of timber bridges from the valid set and total population by year constructed.

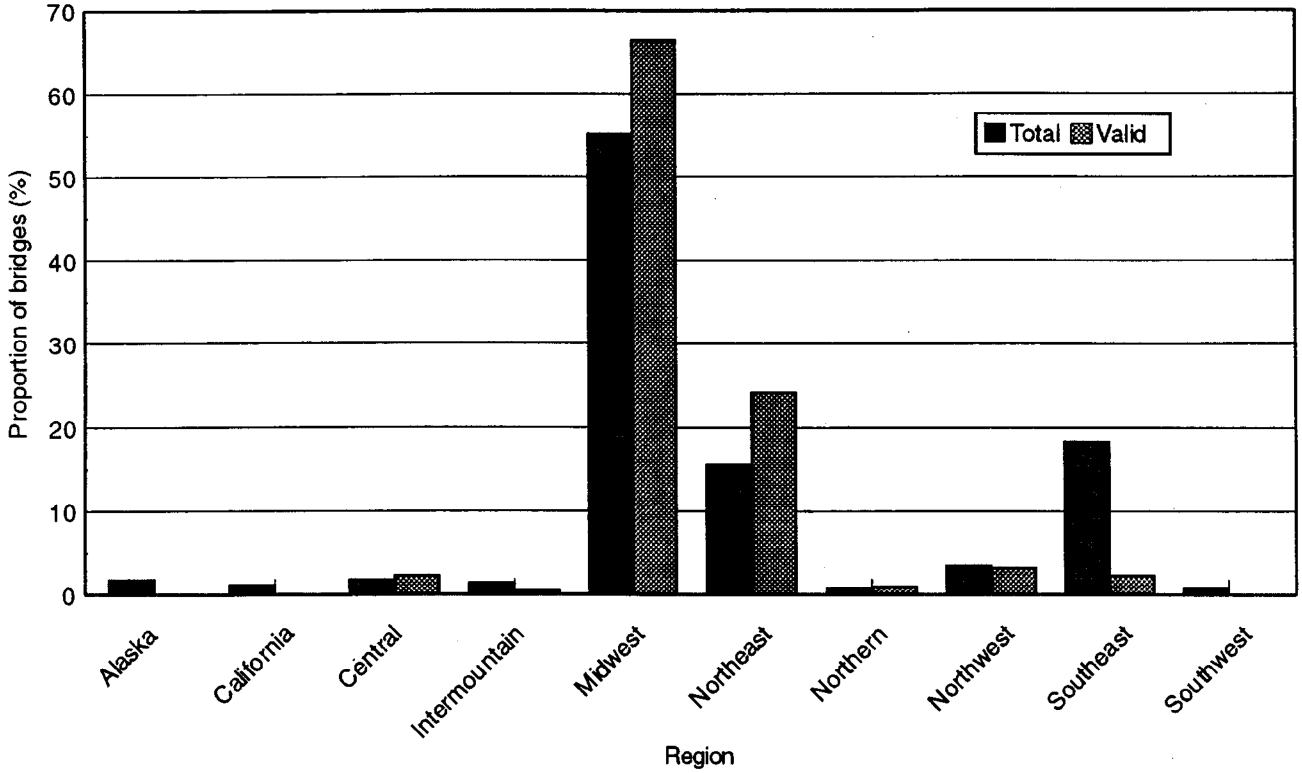


Figure 12—Percentage of timber bridges from the valid set and total population by region.

Appendix E—Cost Analysis

The cost analysis of timber bridge superstructures is described in terms of cost characteristics by single factors and across multiple factors. Figure 13 shows a sample box plot. The boxes represent the middle 50% of data for each category, with the bottom of the box denoting the first quartile (Q1) of data and the top denoting the third quartile (Q3). The horizontal line within each box represents the median for a given category. Lines (whiskers) extend from each box to the lowest and highest value within the region whose lower limit is Q1 − 1.5(Q3 − Q1) and whose upper limit is Q3 + 1.5 (Q3 + Q1). Asterisks designate observations that fall outside this region (outliers).

Figures 14 to 20 show cost trends for construction type, structure length, maximum span length, deck width, load rating, year of construction, and geographic region, respectively. Figures 21 to 35 show costs for two-lane timber bridges for two construction types (slab and stringer/multi-beam) in two regions (Midwest and Northeast). Continuous factors are plotted against cost per square foot. Categorical factors are described using box plots. In addition, data are disaggregated to show trends across multiple factors for a detailed cost analysis.

For comparisons across multiple factors, the Midwest data subset of two-lane slab timber bridges represented four load-rating categories: H10, HS20, HS20+Mod, and HS25 (Fig. 21). The HS20 and HS20+Mod categories were represented by 96 and 18 observations, respectively. The H10 and HS25 categories were each represented by only one observation. Median and mean costs per square foot were lower for HS20 bridges relative to those for HS20+Mod bridges. Cost ranges for the middle 50% of the data set were narrow, with a spread of $8.98 for HS20 bridges and $13.15 for HS20+Mod bridges, compared with $14.53 and $24.91, respectively, for the same load-rating categories from the valid data set (Fig. 18).

The Northeast data subset of two-lane slab timber bridges were represented by only HS20 and HS20+Mod load-rating categories (11 and 4 observations, respectively). The HS20 bridges exhibited a lower median cost relative to that for HS20+Mod bridges (Fig. 22). In addition, mean cost was lower for HS20 bridges ($34.31) than for HS20+Mod bridges ($36.98).

For HS20 bridges, the Midwest region was represented by 96 observations and the Northeast region by 11 observations. For HS20+Mod bridges, the Midwest was represented by 18 observations and the Northeast by 4 observations. For both the HS20 and HS20+Mod data subsets, mean and median costs per square foot were lower for the Midwest than for the Northeast (Figs. 23 and 24, respectively).

A comparison of cost per square foot and structure length for HS20 slab timber bridges in the Midwest exhibited a parabolic trend similar to that for the timber bridge valid data set (Fig. 25). Despite the level of disaggregation, data were still widely variable across structure lengths. Cost values for HS20+Mod slab timber bridges from the Midwest were also widely variable across structure lengths (Fig. 26). The limited number of data points available made it difficult to assess any trend for this cross section. As previously indicated, data were limited for HS20 and HS20+Mod slab timber bridges in the Northeast region. For both HS20 and HS20+Mod bridges, plots of cost per square foot values of cost against structure length showed extreme variability (Figs. 27 and 28, respectively).

The four load ratings available in the Midwest data subset of two-lane stringer/multi-beam timber bridges—H15, H20, HS20, and HS20+Mod—were represented by 3, 4, 10, and 3 observations, respectively. Median cost per square foot increased as load rating increased (Fig. 29). Mean values followed this trend, ranging from $7.73 to $46.91/ft^2. Especially pronounced was the lower median cost per square foot of the HS20 bridges compared with that of the HS20+Mod bridges. The middle 50% of these data for each category also followed this trend.

The four load ratings in the Northeast data subset of two-lane stringer/multi-beam timber bridges were the same as those in the Midwest data subset. The HS15, H20, HS20, and HS20+Mod load ratings were represented by 1, 2, 8, and 4 observations, respectively. Median and mean cost per square foot increased as load rating increased for all but the HS15 category (Fig. 30). As with the Midwest region, the middle 50% of the Northeast data for each category followed the general trend of higher cost for higher load ratings.

The five regions (Central, Midwest, Northern, Northeast, Northwest) in the HS20 data subset of two-lane stringer/multi-beam timber bridges were represented by 1, 10, 1, 8, and 3 observations, respectively (Fig. 31). Mean and median costs were lowest for the Midwest, higher for the Northwest, and highest for the Northeast. The middle 50% of these data for each category followed this trend.

The Midwest and Northeast regions in the HS20+Mod data subset of two-lane stringer/multi-beam timber bridges were represented by 3 and 4 observations, respectively. Median cost per square foot for the Midwest was greater than that for the Northeast (Fig. 32). However, the mean cost for the Midwest was lower than that for the Northeast ($46.91 compared with $54.50). In addition, the range of the middle 50% of these data for the Northeast region was broader and overlapped that of the Midwest region.

Data on cost as a function of structure length for HS20 stringer/multi-beam timber bridges in the Midwest showed a parabolic trend, with higher costs for shorter bridges and lower costs for longer bridges (Fig. 33). Again, data were variable across structure lengths. Only three data points were available for HS20+Mod stringer/multi-beam bridges for the Midwest (Fig. 34). Plots of cost per square foot against structure length were also highly variable for HS20 bridges in the Northeast region (Fig. 35).

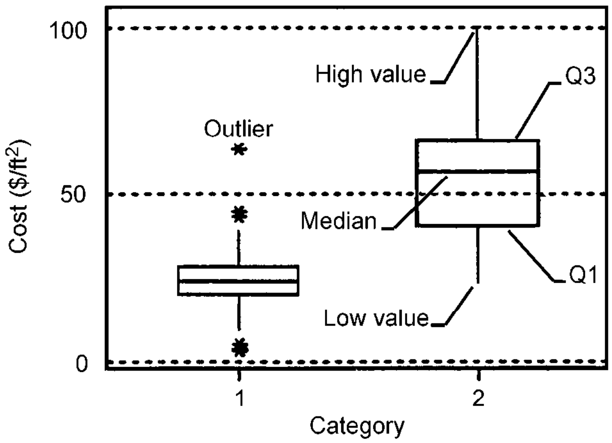


Figure 13—Description of box plot.

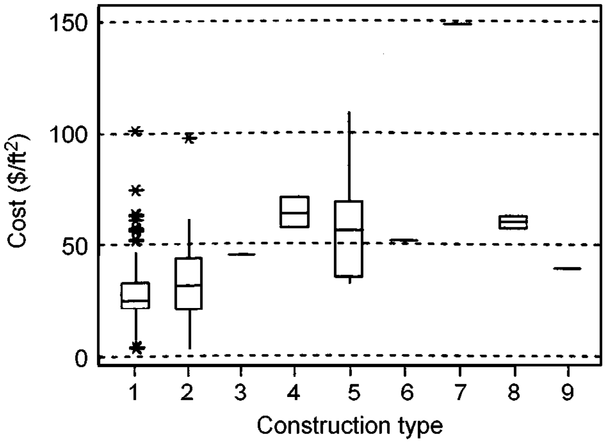


Figure 14—Cost per square foot by construction type: (1) slab, (2) stringer/multi-beam, (3) girder and floor beam, (4) T beam, (5) box beam, multiple, (6) box beam, single or spread, (7) frame, (8) truss, through, and (9) arch, deck.

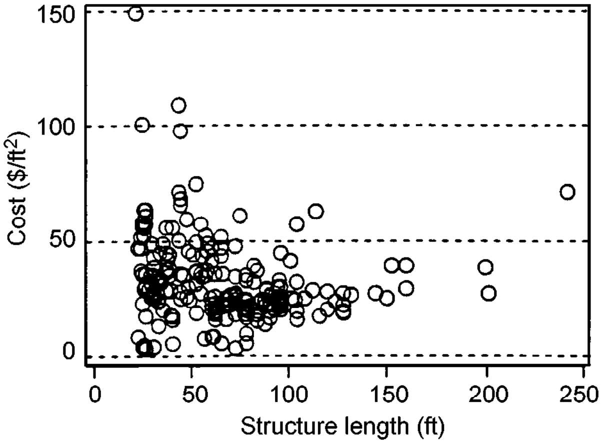


Figure 15—Cost per square foot by structure length.

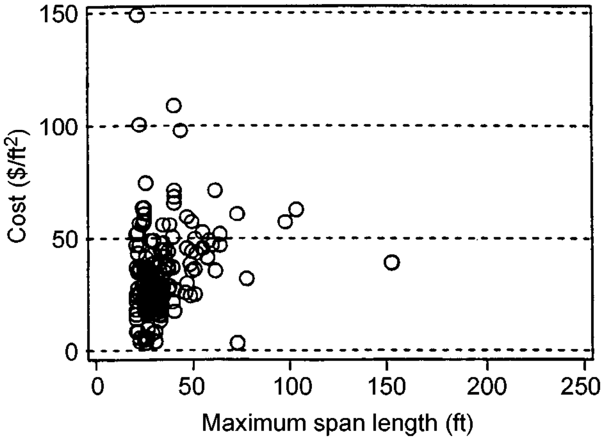


Figure 16—Cost per square foot by maximum span length.

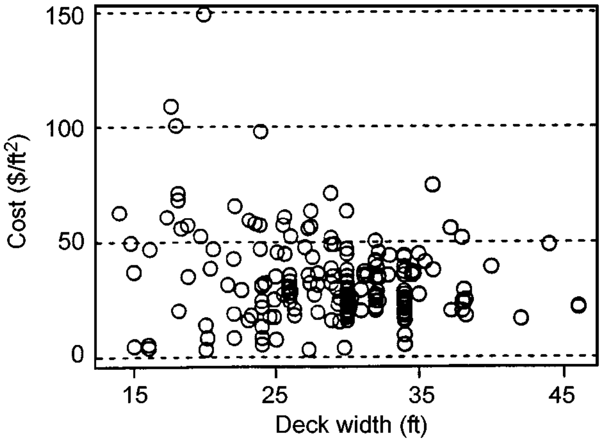


Figure 17—Cost per square foot by width.

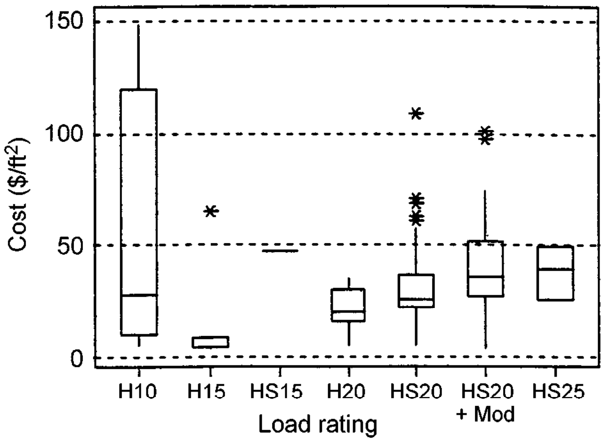


Figure 18—Cost per square foot by load rating.

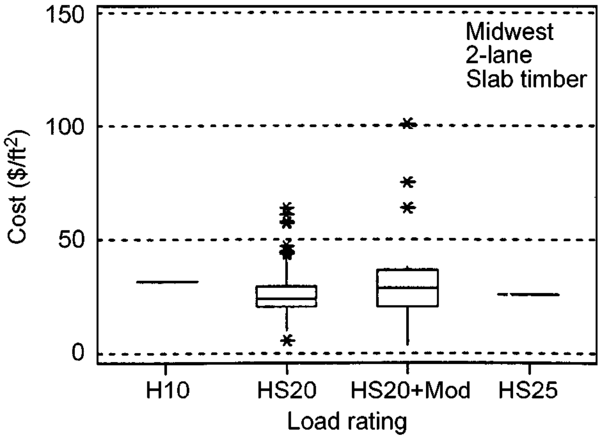


Figure 21—Cost per square foot by load rating for two-lane slab timber bridges located in the Midwest region.

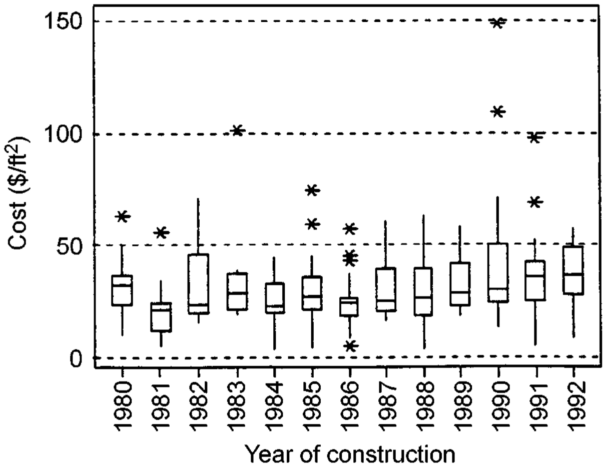


Figure 19—Cost per square foot by construction year.

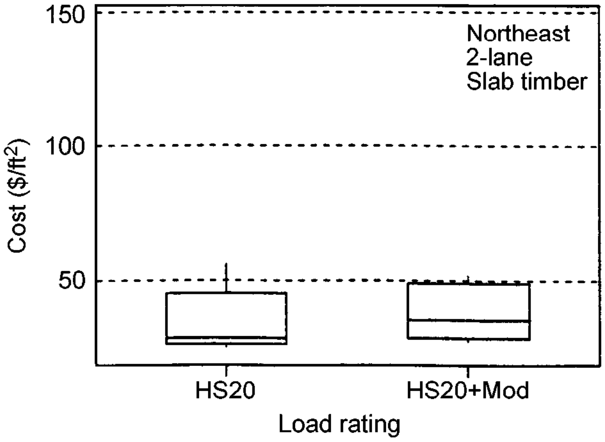


Figure 22—Cost per square foot by load rating for two-lane slab timber bridges located in the Northeast region.

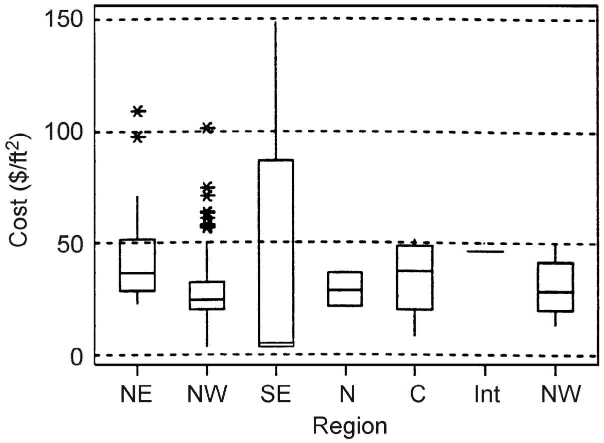


Figure 20—Cost per square foot by region. NE is Northeast, MW Midwest, SE Southeast, N Northern, C Central, Int Intermountain, and NW Northwest.

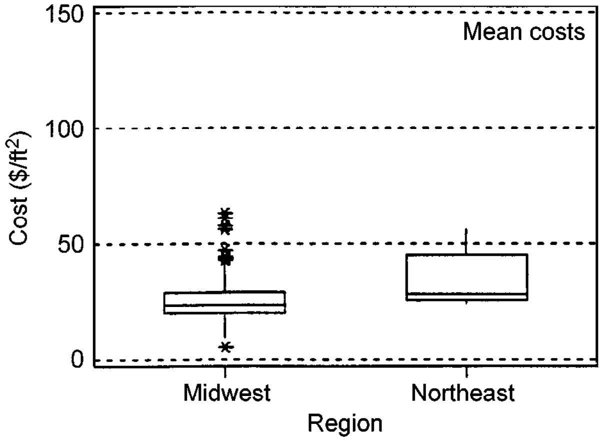


Figure 23—Cost per square foot by region for two-lane, slab, HS20 timber bridges.

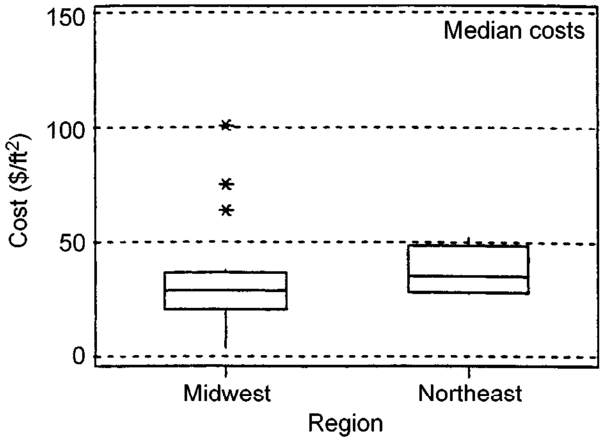


Figure 24—Cost per square foot by region for two-lane, slab, HS20+Mod timber bridges.

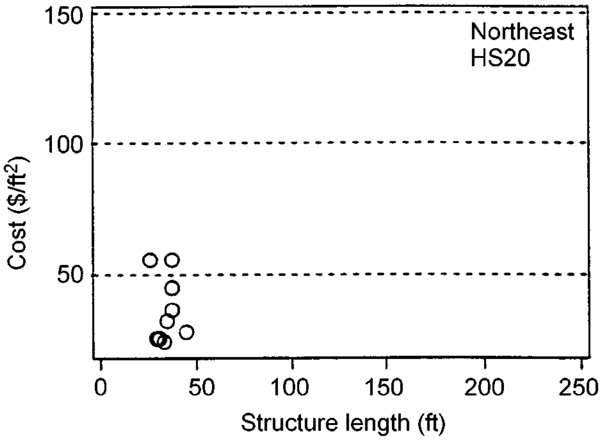


Figure 27—Cost per square foot by structure length for two-lane slab HS20 timber bridges located in the Northeast region.

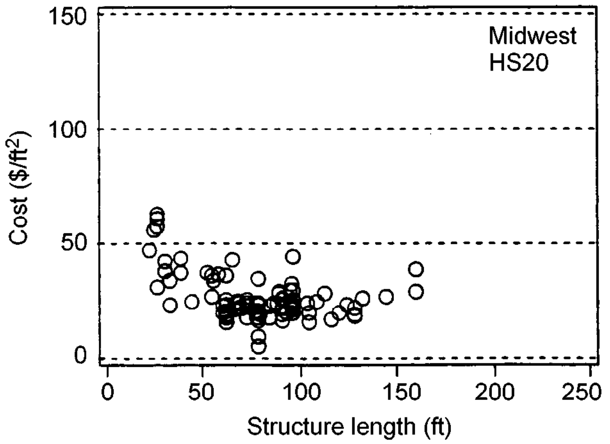


Figure 25—Cost per square foot by structure length for two-lane slab HS20 timber bridges located in the Midwest region.

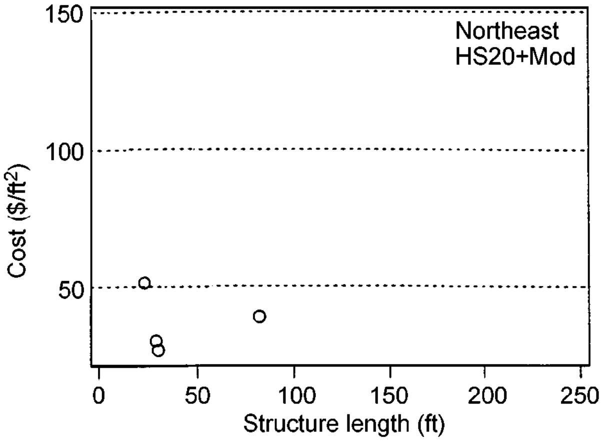


Figure 28—Cost per square foot by structure length for two-lane slab HS20+Mod timber bridges located in the Northeast.

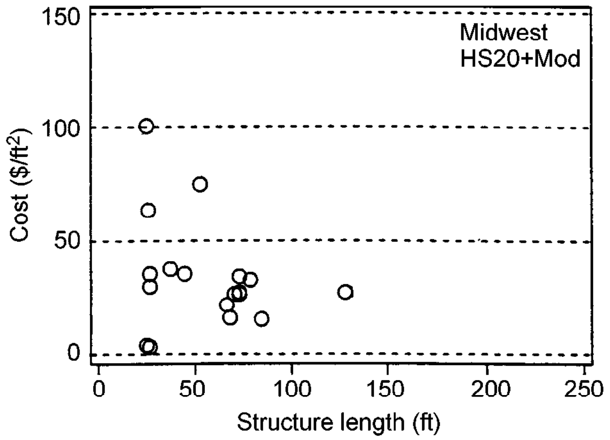


Figure 26—Cost per square foot by structure length for two-lane slab HS20+Mod timber bridges located in the Midwest.

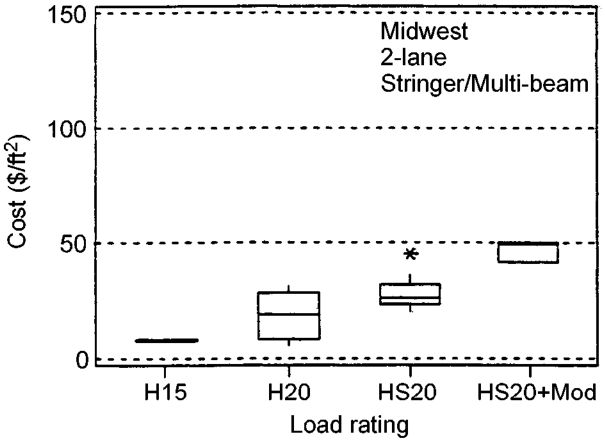


Figure 29—Cost per square foot by load rating for two-lane stringer/multi-beam, timber bridges located in the Midwest region.

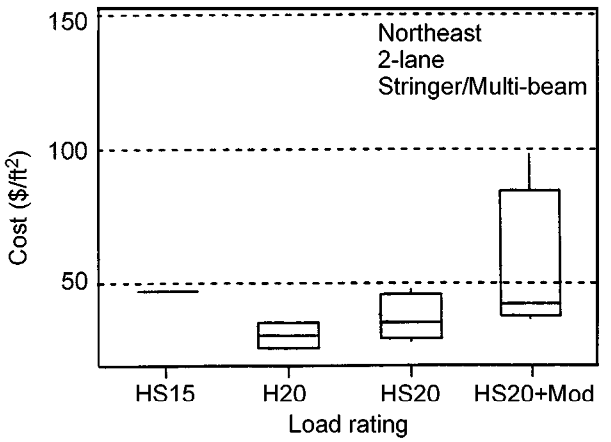


Figure 30—Cost per square foot by load rating for two-lane, stringer/multi-beam, timber bridges located in the Northeast region.

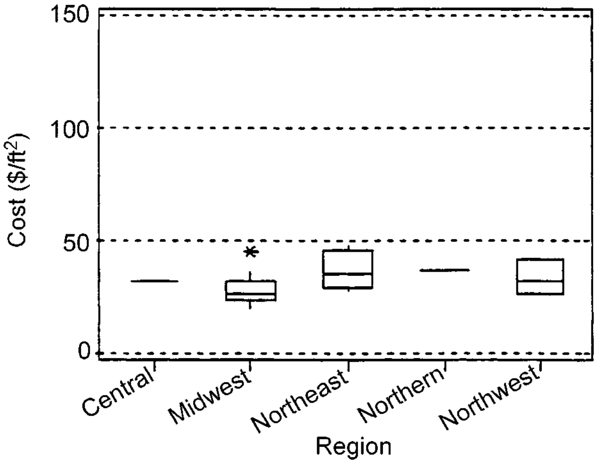


Figure 31—Cost per square foot by region for two-lane, stringer/multi-beam, HS20 timber bridges.

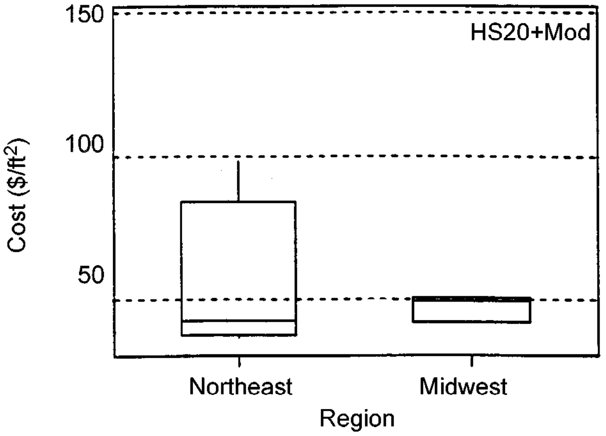


Figure 32—Cost per square foot by region for two-lane, stringer/multi-beam, HS20+Mod timber bridges.

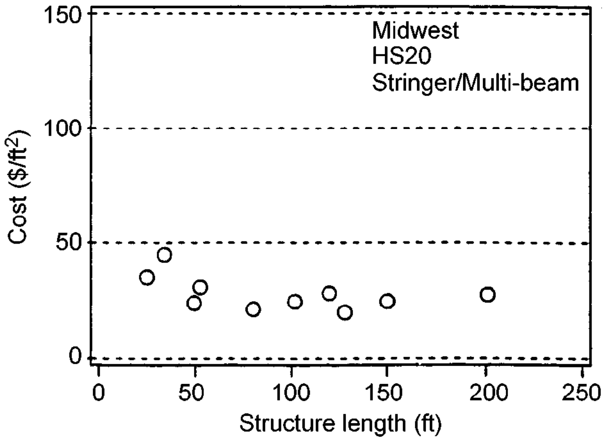


Figure 33—Cost per square foot by structure length for two-lane, stringer/multi-beam, HS20 timber bridges located in the Midwest region.

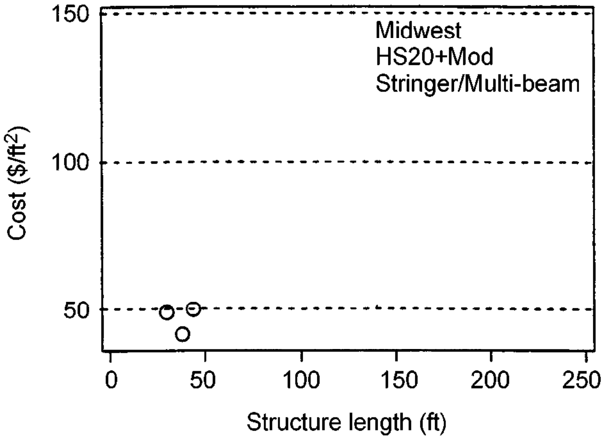


Figure 34—Cost per square foot by structure length for two-lane, stringer/multi-beam, HS20+Mod timber bridges located in the Midwest region.

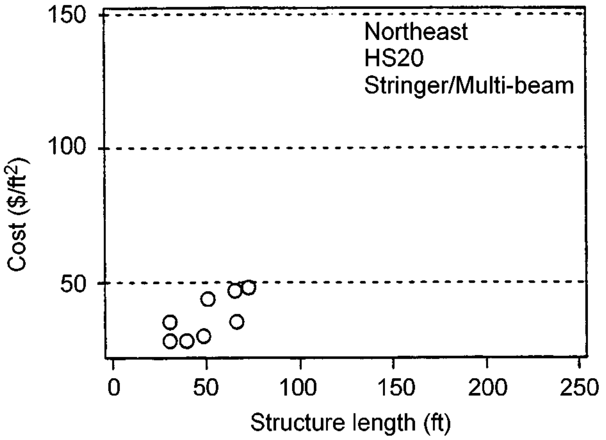


Figure 35—Cost per square foot by structure length for two-lane, stringer/multi-beam, HS20 timber bridges located in the Northeast region.

Appendix F—Verification of Valid Data Set for Matching Bridges

Responses were received for 477 of the original 2,549 matched bridges. Of these, only 190 questionnaires included complete information on cost. The low number of responses was obtained despite repeated mailings to transportation owner–agencies.

Figure 36 shows the percentage of nontimber bridges in the valid data set and total population by material type. Despite the low response rate, characteristics of the valid data set matched those of the total population for material type, with slight deviations for concrete and prestressed concrete bridges.

For each material type, the construction type distribution for the valid data set was similar to that of the total population (Figs. 37 to 39). Of interest was the shift in predominance of one construction type or another. For example, slab bridges accounted for a large portion of the concrete bridges, fewer of the prestressed concrete bridges, and none of the steel bridges, as might be expected.

Structure length characteristics of the valid data set approximated those of the total population for steel, concrete, and prestressed concrete matched bridges for most categories (Figs. 40 to 42). Major exceptions were noted, however, in the 50- to 80-ft range for steel bridges, the 30- to 40-ft category for concrete bridges, and the 30- to 40-ft and 50- to 60-ft categories for prestressed concrete. In these categories, the characteristics of the total population were either over- or underrepresented in the valid data set.

With only a few exceptions, width characteristics for the valid data set matched those for the total population. Values for the valid data set matched those for the total population, with the exception of some overrepresentation in the valid data set of concrete bridges in the 25- to 35-ft range and in the valid data set of prestressed concrete bridges in the 35- to 40-ft range (Figs. 43 to 45).

The number of lanes of bridges in the valid data set followed that in the total population of steel, concrete, and prestressed concrete bridges, with the exception of a lack of representation of single-lane bridges in the valid data set for concrete and prestressed concrete bridges (Figs. 46 to 48). Note that single-lane bridges constituted less than 1% of the total population of concrete and prestressed concrete bridges and that similar underrepresentation was observed for timber bridges for this category.

With few variations, the load rating trend of the valid data set followed that of the total population of steel, concrete, and prestressed concrete bridges. Values for the valid data set roughly matched those for the total population for each material type (Figs. 49 to 51). Exceptions include a lack of representation for H15 steel bridges and H10, H15, and H20 concrete bridges. However, these categories accounted for only small portions of the total population of each material type.

A comparison of steel, concrete, and prestressed concrete bridges by construction year yielded more pronounced differences between the valid data set and total population than were apparent for the other factors considered. Both under- and overrepresentation occurred in the valid data set in various years (Figs. 52 to 54). The reason for such deviations is unknown.

The valid data set matched the total population of steel, concrete, and prestressed concrete bridges for most regions (Figs. 55 to 57). Anomalies included a lack of representation in the valid data set for the Intermountain, Northern, and Southeast regions for all material types and for the Northwest region for steel bridges. Lack of representation in the valid data set occurred for categories that constituted only a small portion of the total population for each material type.

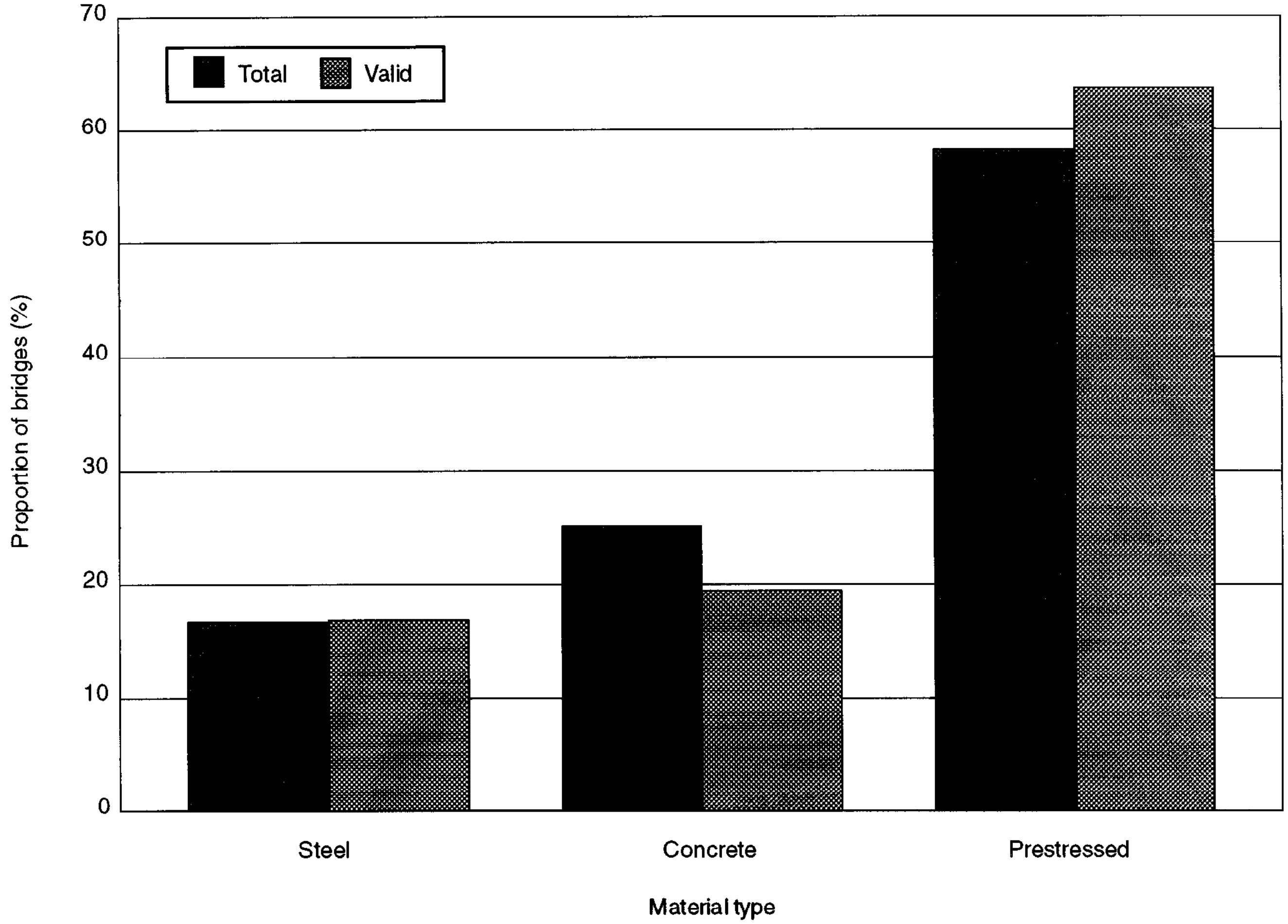


Figure 36—Percentage of nontimber bridges from the valid set and total population by material type.

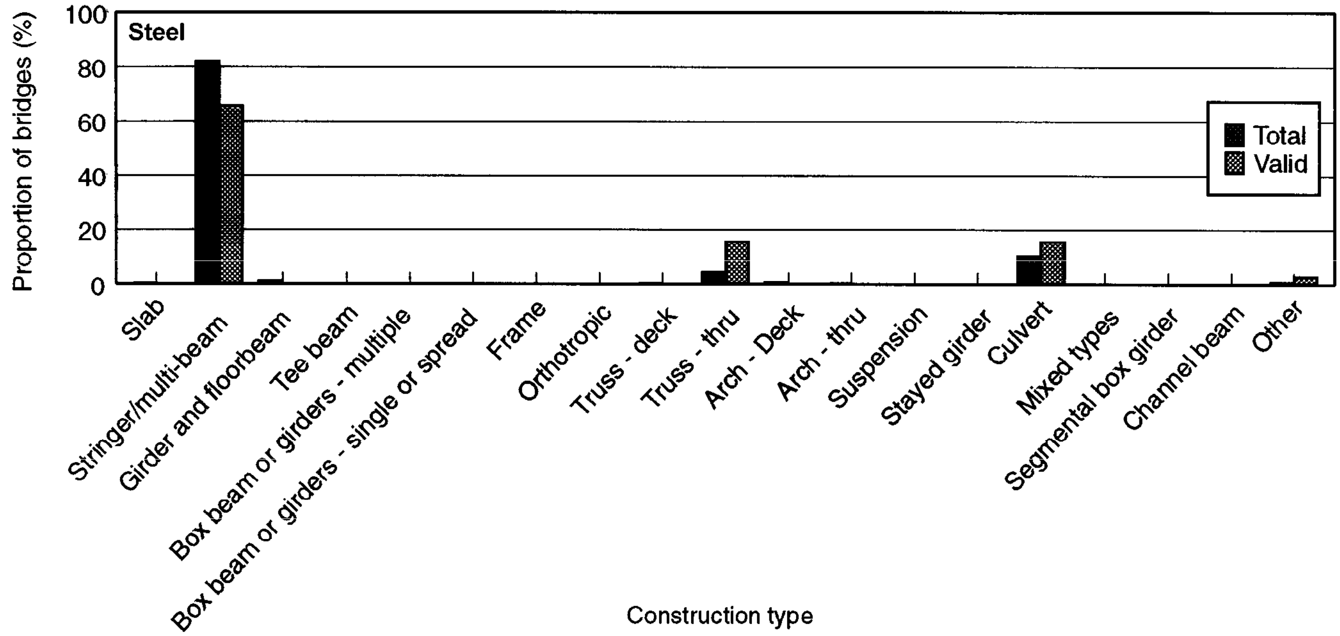


Figure 37—Percentage of steel bridges from the valid set and total population by construction type.

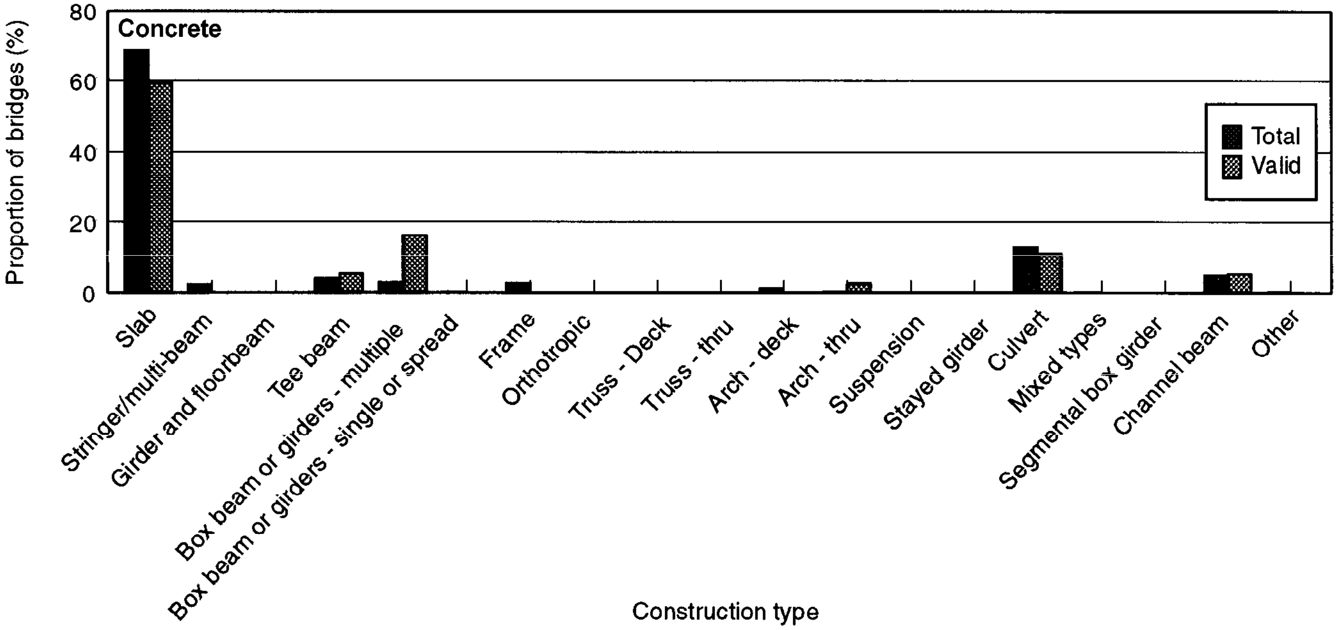


Figure 38—Percentage of concrete bridges from the valid set and total population by construction type.

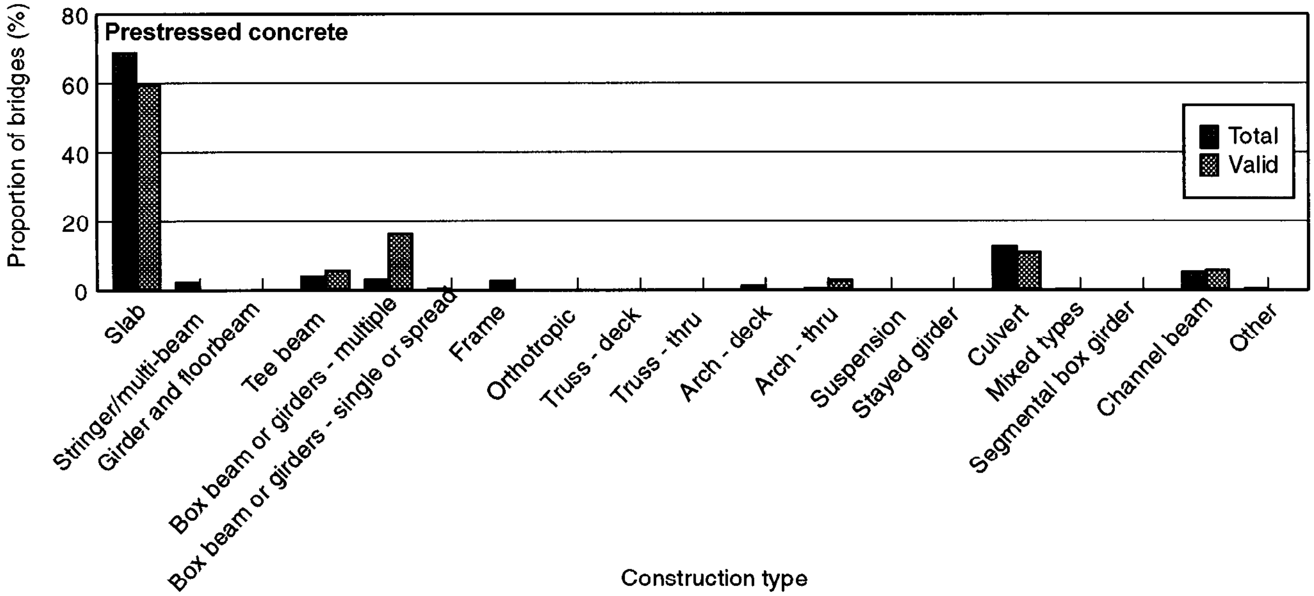


Figure 39—Percentage of prestressed concrete bridges from the valid set and total population by construction type.

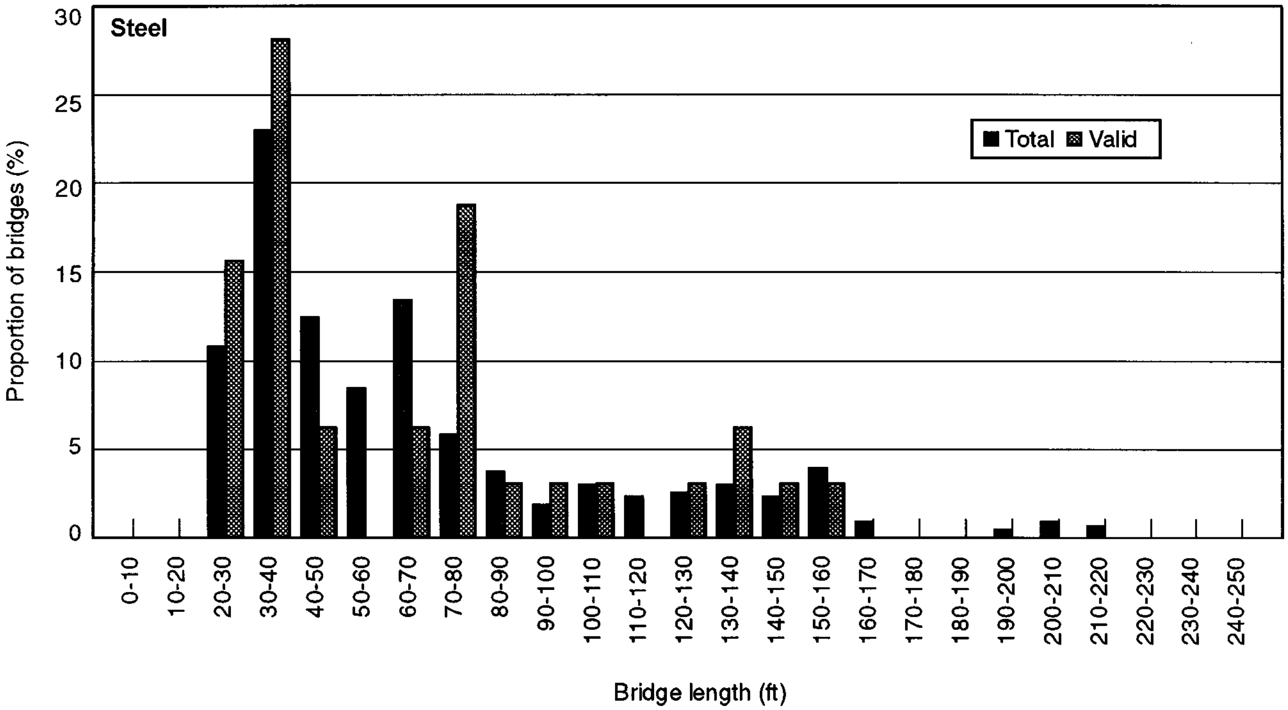


Figure 40—Percentage of steel bridges from the valid set and total population by structure length. The lower end-point of each length interval is inclusive (closed). The upper endpoint of each length interval is non-inclusive (open).

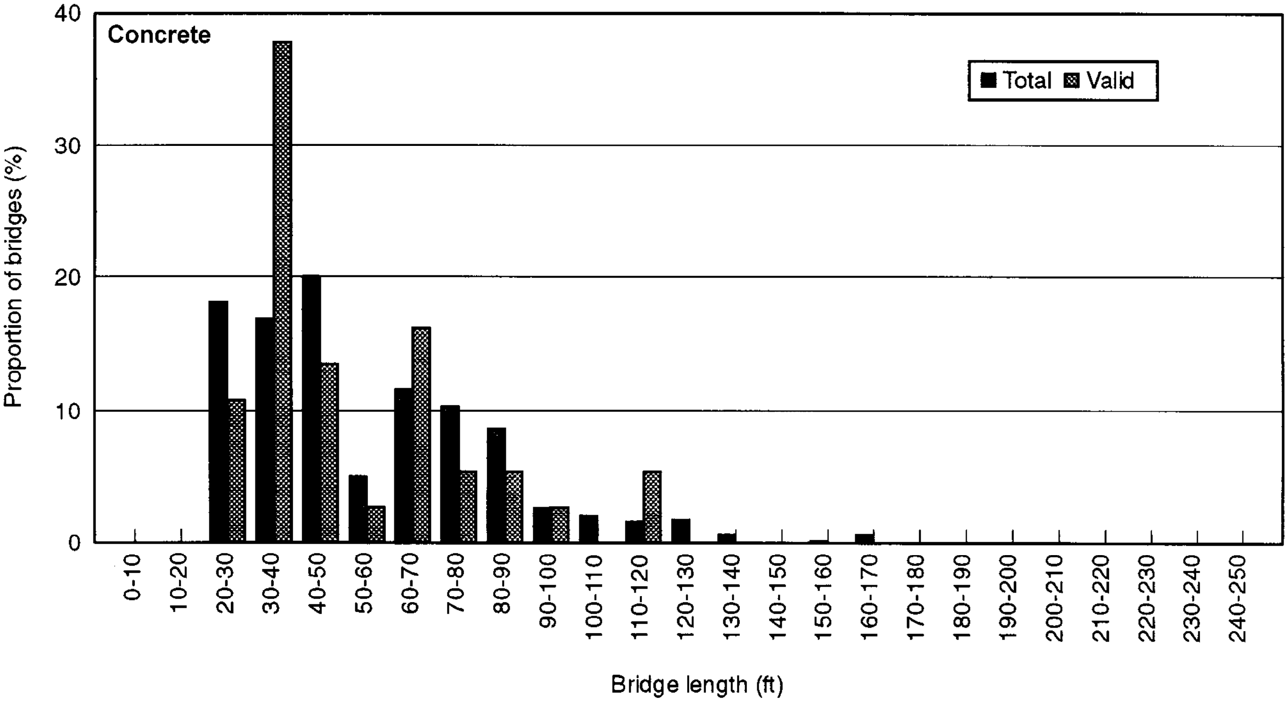


Figure 41—Percentage of concrete bridges from the valid set and total population by structure length. The lower endpoint of each length interval is inclusive (closed). The upper endpoint of each length interval is non-inclusive (open).

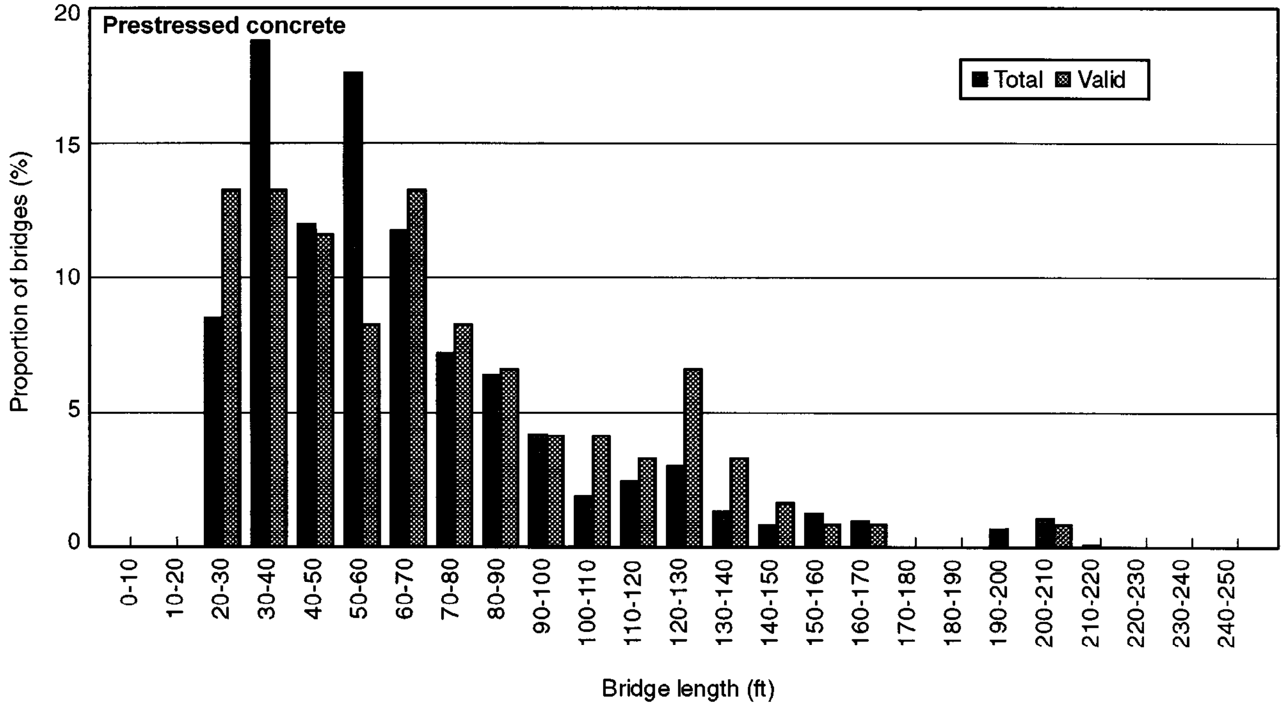


Figure 42—Percentage of prestressed concrete bridges from the valid set and total population by structure length. The lower endpoint of each length interval is inclusive (closed). The upper endpoint of each length interval is non-inclusive (open).

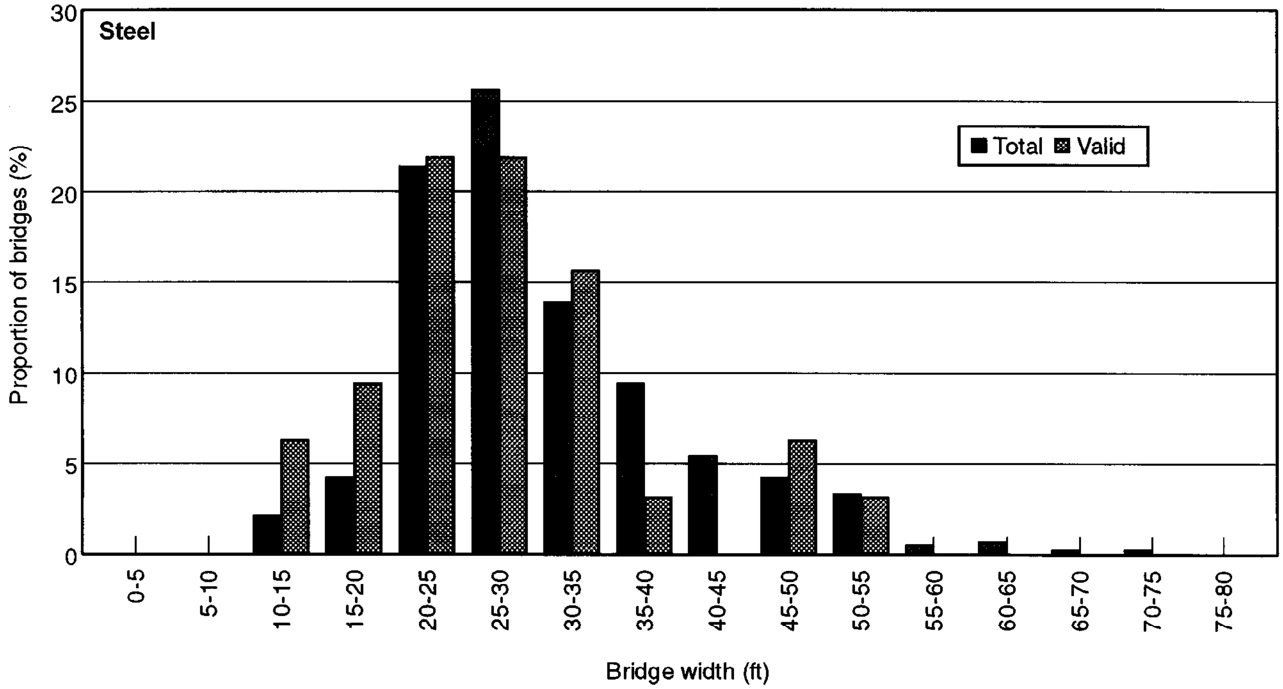


Figure 43—Percentage of steel bridges from the valid set and total population by width. The lower endpoint of each width interval is inclusive (closed). The upper endpoint of each width interval is non-inclusive (open).

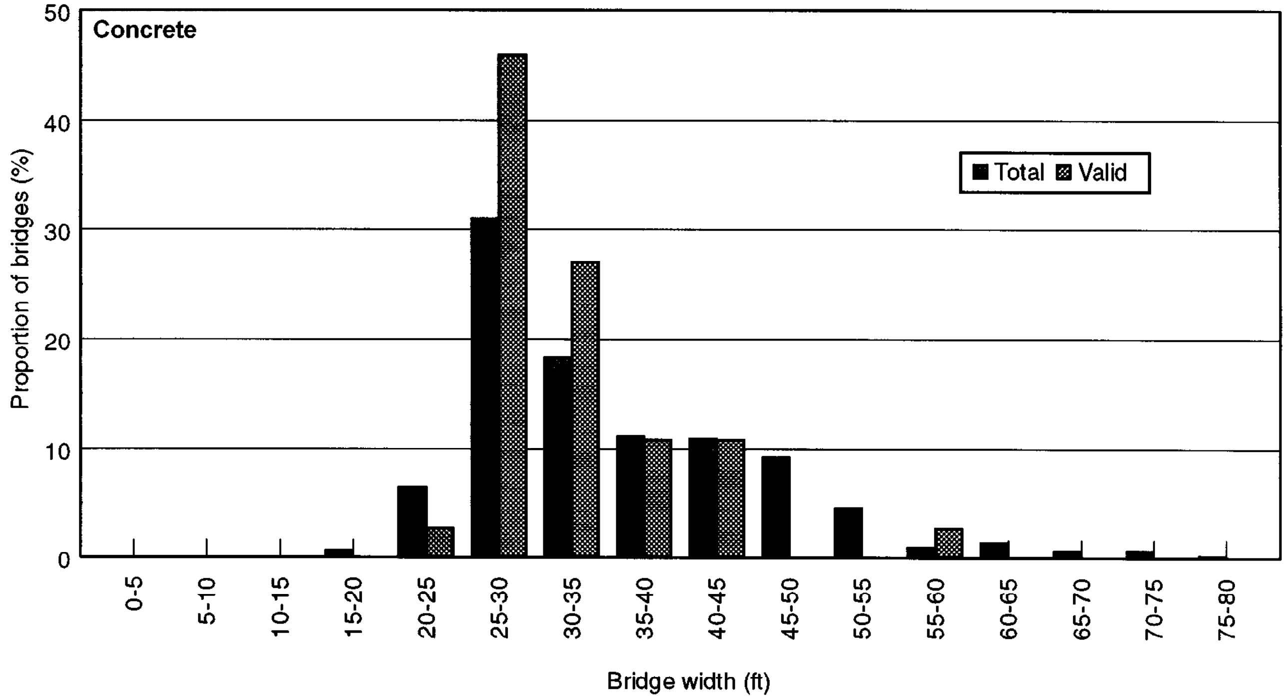


Figure 44—Percentage of concrete bridges from the valid set and total population by width. The lower endpoint of each width interval is inclusive (closed). The upper endpoint of each width interval is non-inclusive (open).

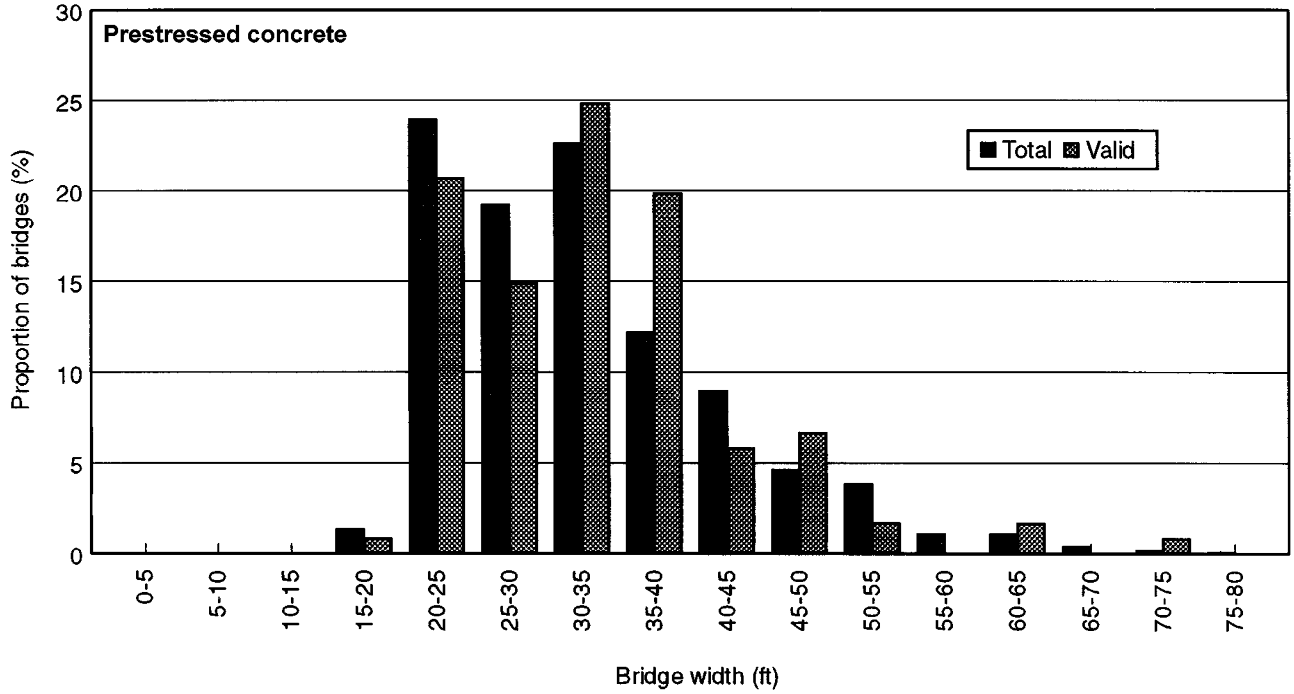


Figure 45—Percentage of prestressed concrete bridges from the valid set and total population by width. The lower endpoint of each width interval is inclusive (closed). The upper endpoint of each width interval is non-inclusive (open).

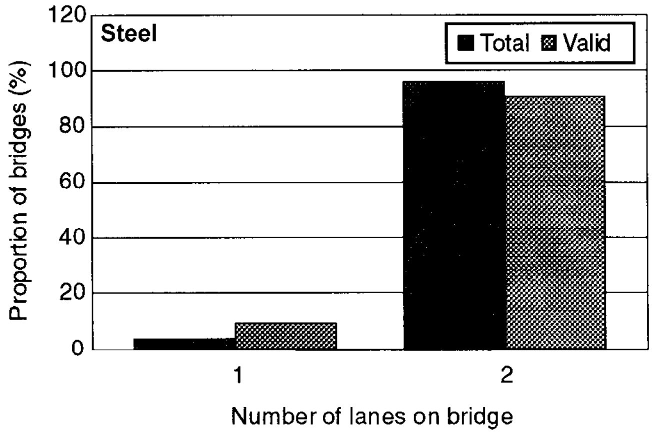


Figure 46—Percentage of steel bridges from the valid set and total population by number of lanes.

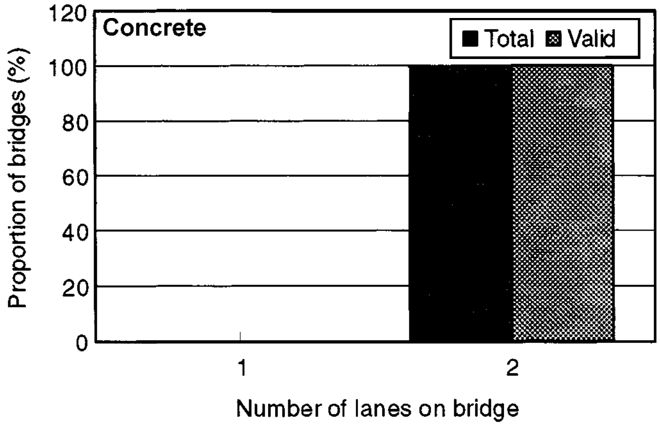


Figure 47—Percentage of concrete bridges from the valid set and total population by number of lanes.

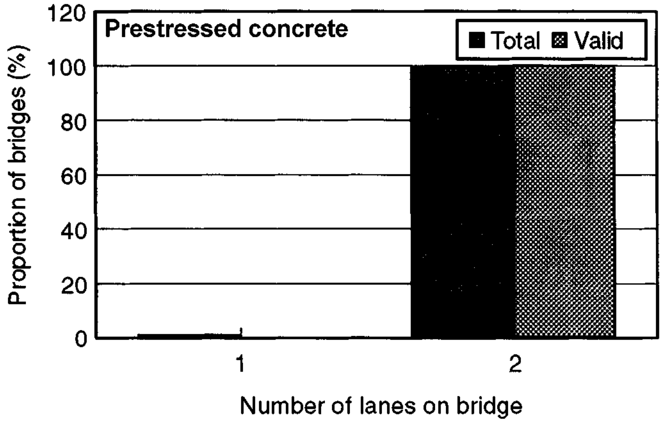


Figure 48—Percentage of prestressed concrete bridges from the valid set and total population by number of lanes.

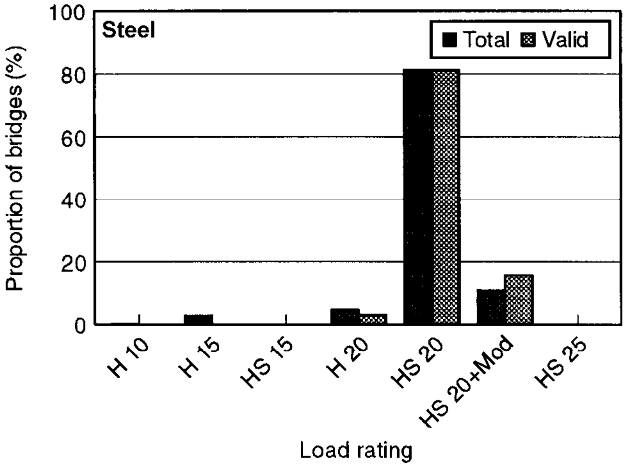


Figure 49—Percentage of steel bridges from the valid set and total population by load rating.

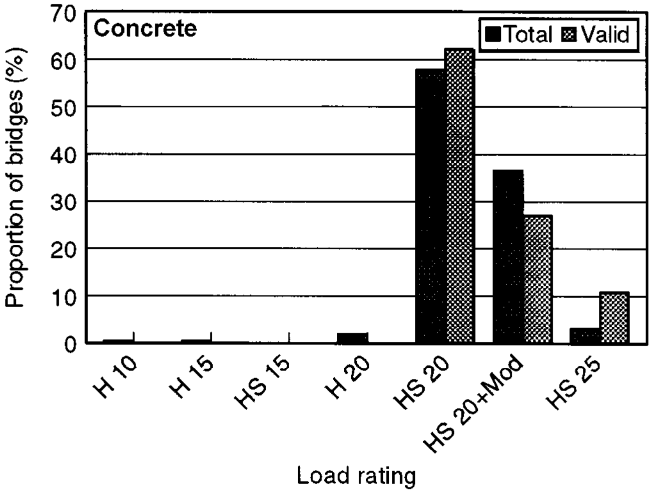


Figure 50—Percentage of concrete bridges from the valid set and total population by load rating.

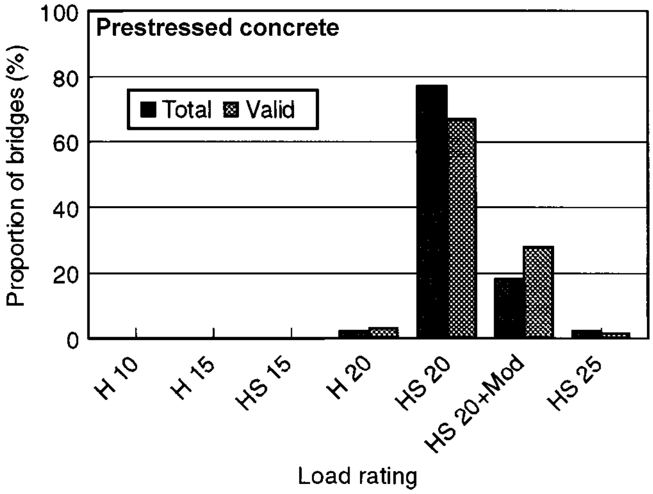


Figure 51—Percentage of prestressed concrete bridges from the valid set and total population by load rating.

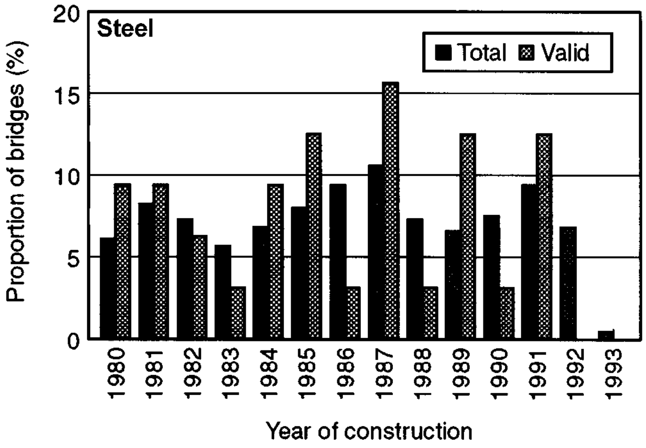


Figure 52—Percentage of steel bridges from the valid set and total population by year constructed.

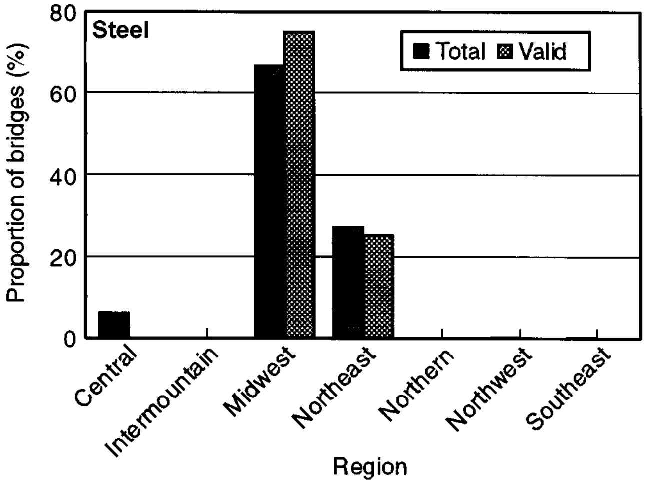


Figure 55—Percentage of steel bridges from the valid set and total population by region.

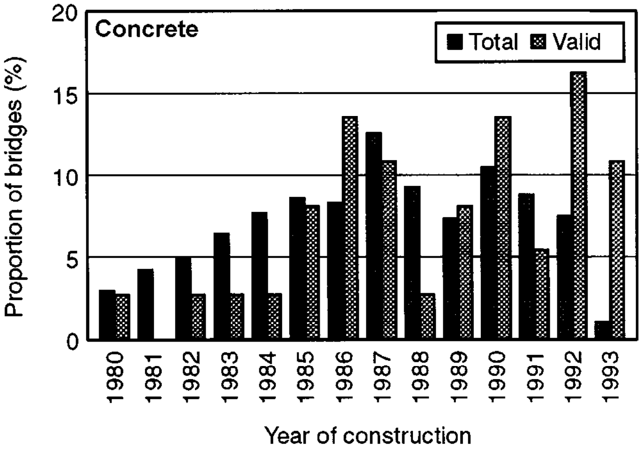


Figure 53—Percentage of concrete bridges from the valid set and total population by year constructed.

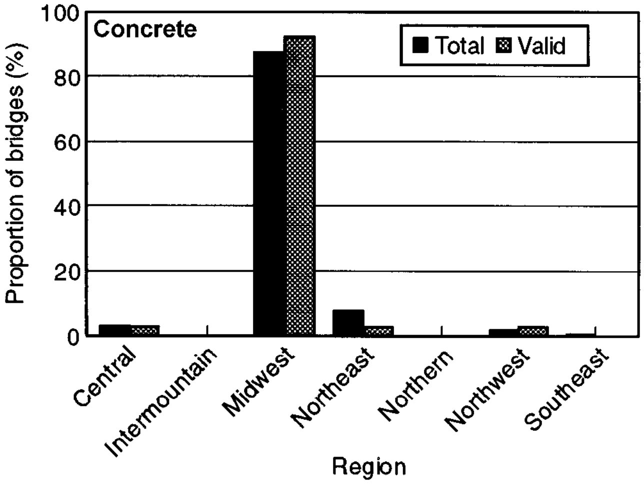


Figure 56—Percentage of concrete bridges from the valid set and total population by region.

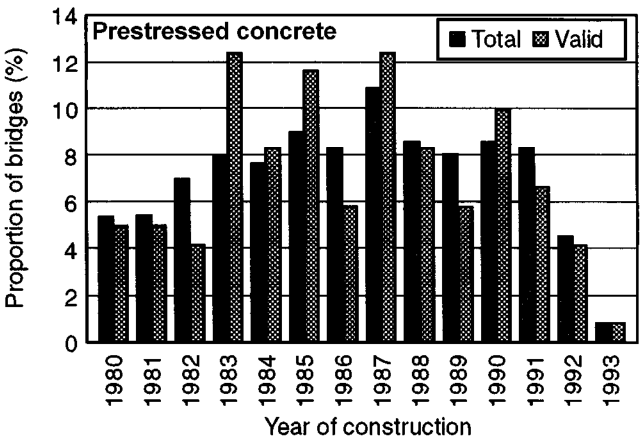


Figure 54—Percentage of prestressed concrete bridges from the valid set and total population by year constructed.

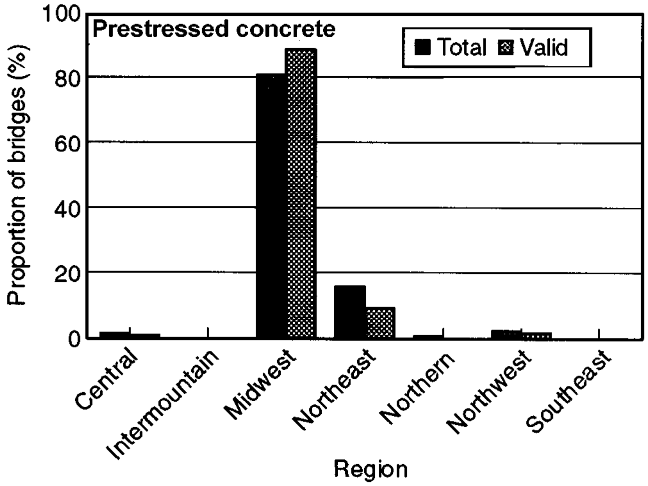


Figure 57—Percentage of prestressed concrete bridges from the valid set and total population by region.