when taking inflation into account (replacement) is calculated as follows:

$3,595/i* = $3,595/0.063 = $57,063.

And the capitalized cost for the choice when inflation is ignored (rehabilitate by force account) is calculated as follows:

$4,722/i = $4,722/0.100 = $47,220.

Therefore, if inflation is ignored in this case, the real present value for the least-cost alternative is understated by nearly $10,000 (17.2 percent).

MICROCOMPUTER PROGRAM

A microcomputer program that simulates the mathematical models presented in this paper and outputs the least-cost solution was written for the Apple IIe. It is a user-friendly prompt-type program that asks for the input parameters (interest rate, if inflation is to be considered; maintenance and rehabilitation costs; time parameters; etc.). The program is available on request from Richard Weyers or Philip D. Cady.

SUMMARY

A standardized cost-effectiveness solution to whether a bridge should be rehabilitated or replaced has been developed. The alternatives were evaluated by means of appropriate mathematical models that have been developed from generalized cash-flow diagrams. Inflation's opposite effects on receipts and disbursements were evaluated and illustrated by an example. The example showed that if inflation is ignored, the wrong decision can be reached and the real cost will be significantly understated. The standardized methodology presented for cost-effectiveness comparison of alternatives for bridge operations should aid in optimizing the use of limited available funds.

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Economic and Performance Considerations for Short-Span Bridge Replacement Structures

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ABSTRACT

Bridges with span lengths up to 100 ft often can be replaced with many different types of structures. This paper is based on a study covering economic and performance aspects of 3,692 bridge replacements in Minnesota during the period 1973 to 1983. Initial and subsequent costs as well as performance problems and considerations for different types of concrete, steel, and timber structures are discussed.

During the past decade new bridge construction and reconstruction activities in the United States have increased significantly. Many different types of structures have been and are being built to replace a large number of deteriorated and deficient bridges. This paper is based on a study that covers 3,692 bridge replacement structures constructed in Minnesota during 1973 to 1983. For the purposes of this study, bridges with main-span lengths of up to 100 ft are considered as short-span structures. Table 1 indicates different types and numbers of bridge replacement structures included in this

TABLE 1 Type and Number of Structures, 1973-1983

Material and Type of Structure	No. of Bridge Structures: State Routes	No. of Bridge Structures: Other Than State Routes
Concrete		
Deck and box girder, rigid frame, arch	1	9
Slab	2	24
Channel	0	59
Culvert		
Box	24	68
Box (precast)	45	98
Pipe (round)	0	8
Pipe arch	75	1,499
Precast arch	4	3
Steel		
Beam	82	251
Truss	6	20
Through, deck, and box girder	6	20
Arch	1	4
Culvert		
Pipe	5	60
Pipe arch	1	280
Long span	8	41
Other	6	17
Prestressed concrete		
Beam	202	88
Slab and voided slab	2	26
Box girder	3	1
Double-T	2	33
Quad-T	0	133
Bulb-T	2	30
Channel and other	0	12
Timber and other		
Timber		
Beam	10	66
Slab	1	327
Box culvert	0	8
Masonry arch	2	11
Wrought iron girder	0	1
Aluminum box culvert	0	5

Note: Construction period 1973 to 1983.

study. Available information on construction costs as well as subsequent performance and required maintenance for these structures are evaluated to determine economic and performance considerations that should justifiably influence the selection of certain types of structures.

AVAILABLE INFORMATION

During the past 11 years, many different types of structures (see Figures 1-4) have been used in replacing 3,692 bridges in Minnesota. For structures other than culverts, construction cost data have been available in terms of contract prices. Tables 2 and 3 give construction costs per square foot for different types of concrete, steel, prestressed-concrete, and timber structures over state trunk highways and routes other than state trunk highways. For culverts, however, construction costs per square foot were not available. Most recent installed costs per linear foot for commonly used types of culverts are presented in Table 4.

Annual inspection reports, field observations, and special reports indicating problems for different types of structures under severe Minnesota conditions were reviewed. History of the type and extent of required maintenance activities as well as information on maintenance costs for different types of structures in different age groups have also been available. This information was analyzed to determine apparent performance patterns, if any, for different types of structures.

ANALYSIS OF AVAILABLE INFORMATION

Concrete Bridge Structures

General Observations

For both trunk highways and other routes, concrete culverts have been used in large numbers as replacement structures. Concrete culverts are relatively simple and quickly constructed and are well suited for rural regions. The Minnesota Department of Transportation has been replacing steel and concrete structures with concrete box culverts (mostly precast) and concrete pipe arches. Slabs and channel sections have been used, although in relatively

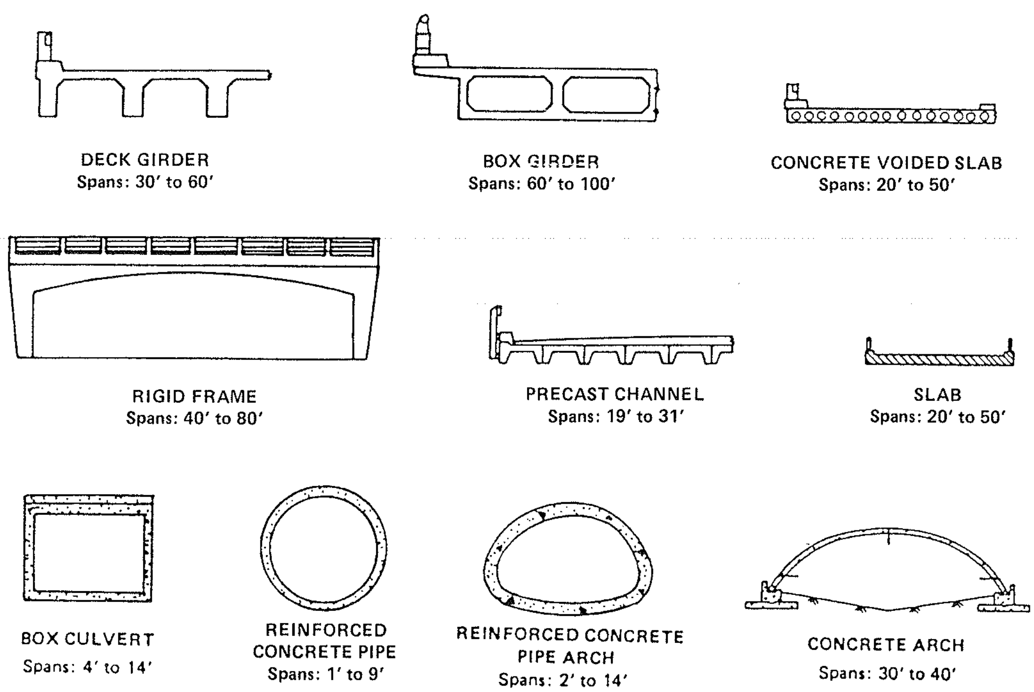

FIGURE 1 Concrete bridge structures.

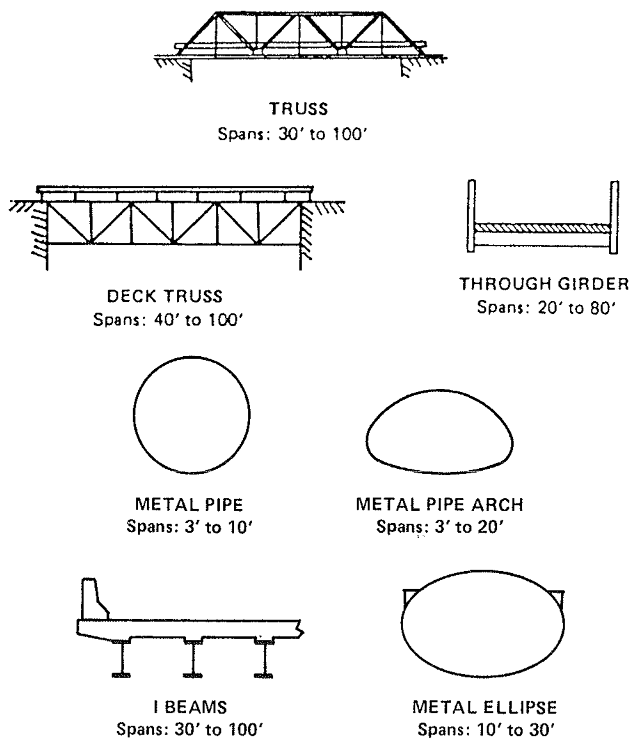

FIGURE 2 Steel bridge structures.

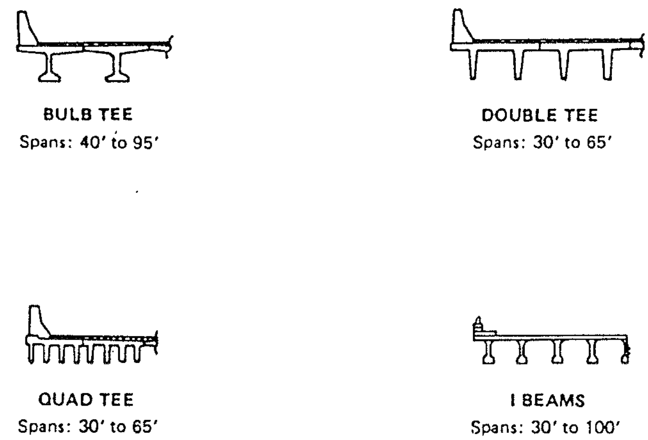

FIGURE 3 Prestressed-concrete bridge structures.

FIGURE 4 Timber bridge structures.

TABLE 2 Construction Cost, 1973-1983: Trunk Highway Bridges

		Type			
Year of Construction	Item	Steel Beam	Steel Continuous Beam	Prestressed Concrete Beam	Timber Beam
1973	Range ($)	32.00-41.00	12.00-27.00	16.00-24.00	15.00-32.00
	Avg ($)	37.50	22.27	19.57	25.20
	No.	4	22	49	5 (pedestrian)
1974	Range ($)	29.00	19.00-48.00	22.00-32.00	
	Avg ($)	29.00	28.00	27.33	
	No.	1	7	18	
1975	Range ($)		26.00-31.00	20.00-32.00	34.00
	Avg ($)		29.25	26.42	34.00
	No.		4	24	1
1976	Range ($)		24.00-46.00	22.00-47.00	
	Avg ($)		33.43	28.21	
	No.		7	48	
1977	Range ($)		22.00-44.00	23.00-43.00	
	Avg ($)		33.80	30.64	
	No.		15	22	
1978	Range ($)		24.00-68.00	25.00-48.00	
	Avg ($)		45.44	34.64	
	No.		18	26	
1979	Range ($)	57.00-127.00	35.00-100.00	29.00-66.00	
	Avg ($)	91.50	58.59	42.69	
	No.	6	17	36	
1980	Range ($)	69.00-112.00	45.00-115.00	54.00-62.00	
	Avg ($)	83.33	69.75	56.80	
	No.	3	17	5	
1981	Range ($)	97.00	44.00-120.00	27.00-94.00	
	Avg ($)	97.00	60.71	54.40	
	No.	1	7	5	
1982	Range ($)	85.00-102.00	28.00-72.00	30.00-61.00	54.00-58.00[a]
	Avg ($)	92.50	49.55	40.57	56.33
	No.	1	22	14	3
1983	Range ($)		40.00-71.00	29.00-70.00	
	Avg ($)		55.24	46.64	
	No.		21	14	

[a]One timber slab bridge was built at a cost of $53.00/ft^2.

TABLE 3 Construction Cost, 1973-1983: Bridges on Other Than Trunk Highways

		Concrete							
Year of Construction	Item	Beam	Continuous Beam	Rigid Frame	Slab	Voided Slab	Box Culvert	Channel Span	Continuous Slab
1973	Range ($)	16.00-28.00	25.00-26.00			31.00-32.00		14.00-29.00	
	Avg ($)	20.66	25.57			31.37		18.44	
	No.	7	1			1		6	
1974	Range ($)	17.00-31.00					38.90	15.00-23.00	
	Avg ($)	21.29					38.90	18.57	
	No.	10					1	7	
1975	Range ($)	21.00-36.00		37.00-38.00	25.17	29.45		27.00-32.00	
	Avg ($)	27.40		37.12	25.17	29.45		24.91	
	No.	6		1	1	1		9	
1976	Range ($)				19.18				22.00-28.00
	Avg ($)				19.18				25.44
	No.				1[a]				4
1977	Range ($)							21.00-38.00	25.00-26.00
	Avg ($)							26.92	25.24
	No.							11	1
1978	Range ($)							27.00-42.00	27.00-32.00
	Avg ($)							33.75	29.22
	No.							4	4
1979	Range ($)						36.51	37.00-43.00	47.00-94.00
	Avg ($)						36.51	40.26	70.75
	No.						1	2	2
1980	Range ($)			157.00-158.00					30.00-38.00
	Avg ($)			157.35					30.29
	No.			1					3
1981	Range ($)	26.00-27.00			77.00-78.00				34.00-35.00
	Avg ($)	26.26			77.51				34.68
	No.	1[c]			1				1
1982	Range ($)	26.26		41.00	26.00				36.00-62.00
	Avg ($)			41.00	26.00				52.00
	No.			1	1				3
1983	Range ($)				72.00-125.00		48.44		
	Avg ($)				98.00		48.44		
	No.				2		1		

[a] RCC pipe arch, related to slab, voided-slab, and box-culvert styles.
[b] Two slab prestressed-concrete bridges were built at a cost of $\$37.76/ft^2$.
[c] Related to beam style.

TABLE 4 Construction Cost, 1982: Culvert Structures

Type of Structure	Size	Cost ($/linear ft)	Size	Cost ($/linear ft)
Concrete				
Box culvert	7 ft x 3 ft	220	12 ft x 9 ft	600
Pipe arch	22 in.	30	169 in.	430
Pipe	12 in.	20	84 in.	160
Precast long-span arch	31 ft	670	40 ft	1,200
Steel				
Pipe (corrugated)	12 in.	10	90 in.	190
Arch (corrugated)	17 in.	10	71 in.	55
Long span (full ellipse)	23 ft	700	30 in.	400

smaller numbers, for county and local bridges. Because of the need for time-consuming falsework, formwork, cure, and field quality control for such construction during Minnesota's limited construction season, there apppears to be a definite trend to minimize or eliminate cast-in-place reinforced-concrete construction. Further, because of their generally better quality and strength, standard prestressed concrete beam sections are being favored over both precast and cast-in-place reinforced-concrete sections.

Economic and Performance Considerations

The cast-in-place reinforced-concrete structures are quite labor intensive, take longer to construct, and generally cost more. This is particularly true in the case of cast-in-place reinforced-concrete beam and deck-girder type structures. For spans up to 50 ft, cast-in-place slab-type structures are simpler to form and support and are less expensive to build as well. Precast channel sections make economical and speedy modular construction possible and eliminate the need for expensive field forming and falsework. These channel sections have been competitive in price for spans up to 30 ft and have been widely used by county and local governments. Since 1979, however, their use has been discontinued because of severe concrete spalling around the reinforcement located in their legs.

A review of required maintenance and cost data for concrete structures in the age groups of 0-10, 11-20, 21-30, and more than 31 years indicates the main problems to be decks and railings. This is especially true for bridges more than 31 years old, for which the maintenance costs have been considerably higher. Better protection of surfaces exposed to winter salt and sand is therefore necessary. This, however, is not critical for concrete culverts because they do not have exposed deck systems.

Steel Bridge Structures

General Observations

Steel beam is the predominantly used section for structures on state routes. They are lighter in weight than concrete and offer possibilities of year-round construction. They can be easily built

Steel				Prestressed Concrete						Timber	
Beam	Deck Girder	Continuous Beam	Continuous Deck Girder	Beam	Voided Slab	Precast Channel	Double-T	Bulb-T	Quad-T	Beam Span	Slab Span
	30.00-31.00 30.38 1			20.00-21.00 20.76 1						15.00-19.00 17.26 6	14.00-15.00 14.43 4
				17.00-28.00 22.82 5		29.00 29.00 1				17.00-20.00 18.60 2	19.00-21.00 19.66 3
				23.00-32.00 25.13 5						21.00-26.00 23.46 3	18.00-38.00 23.59 10
		21.00-26.00 22.83 3	23.00-24.00 23.83 1	21.00-42.00 29.20 9	37.76 37.76 1[b]					25.00-26.00 25.87 1	18.00-24.00 21.23 8
		25.00-41.00 30.88 13		21.00-34.00 30.86 11	44.00-45.00 44.54 1	22.00-29.00 24.99 3			28.00-41.00 31.79 6		20.00-30.00 23.90 32
25.00-29.00 26.69 2		25.00-51.00 35.08 27		25.00-53.00 35.46 12	41.00 41.00 1		27.00-28.00 27.50 1	28.00-56.00 41.97 4	23.00-60.00 32.62 39	26.00-44.00 34.39 9	24.00-35.00 28.79 63
		31.00-54.00 38.40 24		20.00-80.00 39.02 15	35.00-50.00 42.45 2		31.00-42.00 34.86 10	34.00-77.00 44.93 10	29.00-72.00 40.40 33	31.00-32.00 31.39 1	15.00-69.00 28.43 28
		22.00-51.00 38.78 8		61.00-80.00 73.31 3	35.00-36.00 35.59 1		36.00-64.00 36.82 5		33.00-40.00 37.47 6		30.00-45.00 35.43 30
		34.00-46.00 39.15 11		30.00-54.00 38.32 10			24.00-36.00 30.91 5	35.00-37.00 35.86 2	29.00-50.00 34.30 18	54.00 54.00 1	29.00-64.00 36.38 21
		25.00-49.00 38.06 17		34.00-50.00 40.50 6			30.00-43.00 34.13 3	32.00-44.00 35.50 5	29.00-37.00 33.25 8		29.00-46.00 34.27 22
		32.00-57.00 41.57 9		37.00-64.00 41.60 6			27.00-42.00 33.46 5	39.00-44.00 41.70 4	31.00-39.00 34.65 10		30.00-37.00 34.19 8

on large skews and curves and are adaptable to flared geometry. This is a great advantage, especially for state trunk highway bridges. The steel beam sections are widely used for replacement structures on other than state routes as well. However, steel pipe and pipe arch culverts are relatively simple and faster to install and are well suited for rural regions. Therefore, these sections are predominantly used as replacement structures for other than state routes. Steel continuous-beam and plate-girder sections have also been used, although in relatively smaller numbers, for county and local bridges. The fabrication and erection of steel built-up sections require skilled labor and extensive inspection.

Economic and Performance Considerations

The steel beam structure lends itself easily to simplified and faster construction. For county and local structures, therefore, its cost has been quite competitive with costs of prestressed-concrete beam bridges. For state trunk highway bridges, however, the cost appears to be 15 to 20 percent higher than that of prestressed-concrete beam structures. Special skews and curves and flared geometry, which is more common with state trunk highway bridges, could be reasons for such a difference in costs. Corrosion at connections as well as under leaky expansion joints and fatigue cracking at or near welds are of concern in steel structures. Fire and accident damage to critical structural components is also of serious consequence.

A review of the required maintenance and cost data for steel structures in the age group of 0 to 20 years indicates that decks, beams, and joints have the most problems. Subsequently, problems with bearings appear to develop in the age group of 21 to 30 years and with substructures in the category of more than 31 years. In general, well over 50 percent of the maintenance costs relate to decks and beams. Better protection for surfaces exposed to winter salts and better drainage systems are necessary.

Prestressed-Concrete Bridge Structures

General Observations

Use of prestressed-concrete sections for bridge construction in Minnesota has been extensive. Modern precasting, pretensioning, and transportation facilities have made lighter, longer span sections economically available. Such sections are manufactured year-round in plants by using higher-strength concrete and under stricter quality control. The standard beam sections are therefore predominantly used for structures on state routes. Prestressed double-T, bulb-T, and quad-T sections, which were introduced in Minnesota in 1977-1978, do not require any deck forming and make truly modular system bridge construction possible. These sections are widely used for structures on other than state routes.

Economic and Performance Considerations

For structures on state trunk highway routes, prestressed-concrete beams are commonly used. The standard prestressed-concrete beam structures have, in general, been 15 to 20 percent more economical than steel beam structures. Double-T, bulb-T, and quad-T sections, because they eliminate the need for deck forming, have been more economical than prestressed beam sections. Further, the shallower depths of these sections necessitate less extensive grading work for the bridge approaches. This has been particularly important for counties and local governments, because Minnesota bridge funds are not available for approach-grading work. Shallower sections therefore reduce the dollar amounts of local participation as well. Prestressed-concrete beam sections have been used for state trunk highway bridges primarily because of heavy traffic loads and concern over damage to joints if quad-T sections are used.

Double-T and bulb-T sections have also been used for state trunk highway bridges because of their longer span capabilities and less problems from the number of bearings required. These sections are used with 5 to 6 in. of cast-in-place concrete slabs over them to eliminate joint-cracking problems between sections.

A review of required maintenance and cost data for prestressed-concrete structures in the age group of 0 to 10 years does not indicate any major problems. In the age group of 11 to 30 years, however, expansion joints appear to require major maintenance and in the category of more than 31 years beams need major maintenance.

Timber Bridge Structures

General Observations

Timber bridge structures present a natural and aesthetically pleasing appearance. However, their use is somewhat limited to short span lengths. They are seldom used for structures on state trunk highway routes. Timber bridges offer the possibility of year-round construction with basic tools and minimal maintenance costs. Further, they require a much less sophisticated inspection than concrete or steel bridges. Timber beam and slab spans are therefore widely used on local and county routes. They are, however, vulnerable to damage by fire, accidents, and insects.

Economic and Performance Considerations

Of the timber-beam and slab span types commonly used by counties and municipalities, the slab type has been somewhat more economical than the beam type. Although their construction costs are somewhat comparable to sections such as the prestressed-concrete quad-T, their maintenance costs are normally low. Except for icy conditions, the Minnesota environment has not been detrimental to timber bridges. Carefully placed ice breakers and use of slanted members have successfully minimized ice damage. Use of ring-shank nails and similar hardware has successfully prevented lamination of timber members.

A review of required maintenance and cost data does not indicate any major problems for bridges in the age group of 0 to 30 years. In general, major maintenance of timber decks appeared to become necessary for bridges in the category of more than 31 years.

Culvert Structures

General Observations

A variety of concrete and metal culvert types have been commonly used in Minnesota when there is a small stream flow. The soil pH and resistivity determine whether a concrete or a metal culvert would be appropriate for a particular location. Since their introduction in the mid-1970s, longer-span metal culverts have been well accepted by counties and municipalities. They have also been accepted for state trunk highway routes. In 1976, precast concrete box culverts were introduced in Minnesota. These have gained wide acceptance because of their rapid construction. Precast concrete arch sections are particularly suitable when headroom limits the use of round pipe sections. Their wide-bottom shape fits well into small stream bottoms. A new longer-span precast concrete arch type has been recently introduced in Minnesota. This type consists of complete precast arch sections set on cast-in-place concrete footings.

Economic and Performance Considerations

Table 4 gives installed costs for different types of culverts. Precast concrete arch sections have been the most commonly used because of their competitive price, faster construction, and suitability under a variety of soil conditions. The less costly prefabricated metal culverts are appropriate when conditions are less corrosive. Their ability to be assembled away from the site and placed by cranes makes them economical. Concrete floors, headwalls, and dropwalls have been necessary to prevent the scour problems of long-span metal culverts.

Concrete culverts need a good bedding and need to be tied together to alleviate settlement and piping problems. Concrete arch-type culverts have a tendency to fill in under low flow conditions and restrict waterway openings. Inverts of metal culverts disintegrate and need relining or replacement. Also, poor compaction of soil during installation can result in distortion or total failure of metal culverts.

A review of required maintenance of culverts indicates problems to be related to either poor construction practices or scour.

CONCLUSION

Certain definitive patterns have become apparent as a result of this study of 3,692 bridge replacements in Minnesota over the last 11 years. Some of the conclusions are as follows:

1. There is a definite trend away from labor-intensive and time-consuming types of construction;
2. A stronger emphasis exists on precast rather than cast-in-place construction;
3. Although steel beam and prestressed-concrete beams or double-T sections are mostly used for state trunk highway bridges, counties and municipalities have shown their preference for steel beams, quad-T's, and timber spans;
4. Different culvert types not only are a workable alternative but are widely used as economical bridge-replacement structures for state, county, and local routes; and
5. Provisions for adequate protection of surfaces exposed to corrosive environments are necessary to improve bridge performance and reduce future maintenance costs.

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