

# Short Span Highway Bridges with Wide Stringer Spacing and a Two-way Reinforced Concrete Deck

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CONFRONTED WITH the large number of bridges to be constructed as part of the burgeoning highway program that is imposing an additional burden upon the already overburdened fiscal capacity of all levels of government, it is an appropriate time for bridge engineers to examine the factors underlying current bridge practice for the purpose of determining what, if any, alterations of this practice are in order. This determination necessarily requires an evaluation of the trends and possibilities in bridge design, fabrication and erection.

Toward this end a thorough evaluation was made of the current practice and future possibilities in bridge design, fabrication, and erection from which the following conclusions were reached:

- (1) The use of wide stringer spacings with two-way reinforced concrete decks will generally result in substantial savings in cost.
- (2) Continuous spans, even when the spans are quite short, are generally more economical than simple spans.

In making this evaluation little attention was directed to the design specifications, although it appears that some changes may be warranted, particularly in the area of two-way slab design. In addition no consideration was given to bridges with spans of over 100 ft, since by far the greatest majority of money spent on bridges is spent on bridges with spans of less than 100 ft. However some of the principles that evolved would have application for spans over 100 ft.

Part 1 of this paper will deal with design investigations for a 180 ft-0 in. portion of a bridge which has a total length of 822 ft-3 in. This portion of the design was selected because it embodies all of the design decisions that evolved from the evaluation of current bridge practice. Unfortunately because of roadway changes and

other unavoidable circumstances, this bridge had to be redesigned and no validation of the estimated savings shown in Part 1 is possible.

Part 2 contains the results of letting to contract 12 bridges using this system. These results are compared to costs for other steel stringer bridges of similar spans using standards of the Oklahoma State Highway Department. The economies achieved exceeded the most optimistic estimates of the Department.

## BACKGROUND

The idea for the use of wide stringer spacings and a two-way reinforced slab developed from the rather startling reduction in steel weight (and consequent costs) that resulted from a reduction in the number of stringers from 5 to 4 on an Oklahoma State Highway standard. The roadway width on this particular standard was 30 ft-0 in. It was reasoned that, if a saving could be realized by reducing the number of stringers from 5 to 4, would it not then be possible to achieve even more economy by supporting a 30 ft-0 in. roadway bridge with 3 stringers?

It was proposed that for a 30 ft -0 in. roadway bridge a 13 ft-0 in. stringer spacing be used and that the concrete deck be reinforced in two directions to minimize the necessary slab thickness. After considerable investigation, and discussions between the consultant, Treat Engineering Company (now Pearson-Chase & Associates), the Oklahoma State Highway Department and the Bureau of Public Roads, it was decided that the consultant could proceed with final designs and plans based on stringer spacings varying between 12 and 15 ft, and using reinforced concrete decks that were reinforced in two directions. Changes in roadway criteria eventually ruled out the use of wide stringer spacings on some of the bridges in the consultant's contract, so that only 14 bridges with stringer spacings varying between 12 ft-0 in. and 14 ft-6 in. were designed in this manner.

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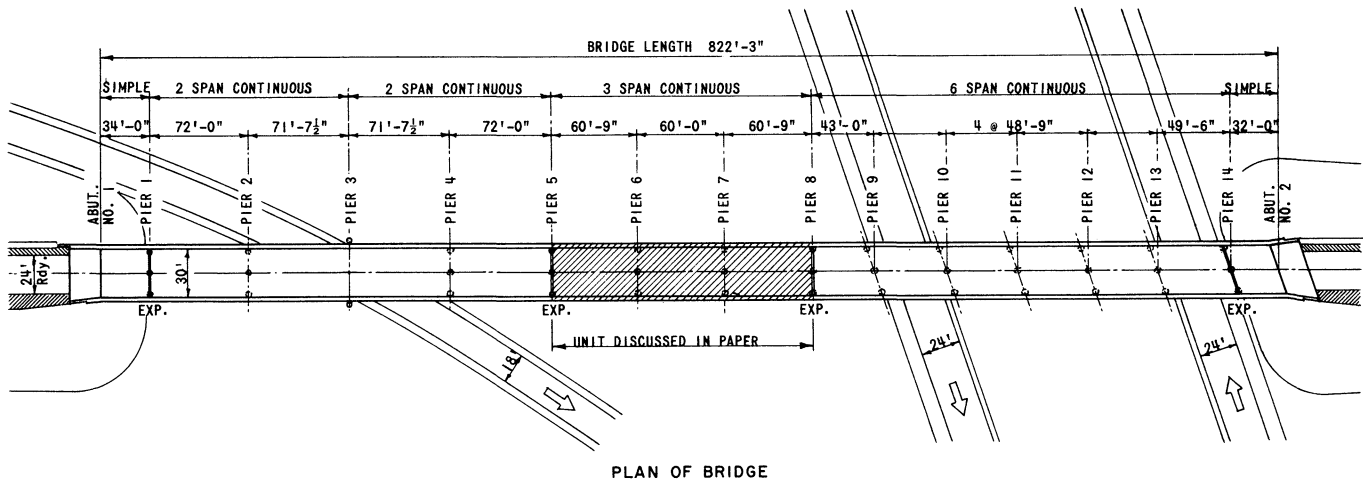


Fig. 1. Plan of bridge discussed in Part 1. Revision of roadway width caused this bridge to be redesigned using 8 ft-6 in. stringer spacing.

### PART I—A PRELIMINARY COMPARISON

In a sense wide stringer spacing is a consideration that could be discussed apart from the two-way reinforced concrete deck, since wide stringer spacing is quite commonly used on long span (over 100 ft) bridges and occasionally used on short span bridges where the live load is less than H20-S16. In both situations it is generally used in conjunction with a floor beam system to support a one-way, longitudinally reinforced concrete deck. In such instances the magnitude of the savings effected by using a wide stringer spacing and reducing the number of stringers more than pays for the added cost of the floor beam system. However, for short span bridges designed for an H20-S16 load this is not true and, therefore, current practice for short span bridges is to have stringer spacings of from 6 ft-6 in. to 9 ft-0 in. with the concrete deck resting directly on the stringers and reinforced to span the stringer spacing. In order to gain a saving from the use of wide stringer spacing on short span bridges it was necessary to employ a two-way reinforced concrete deck, a structural system quite common in building design but rarely, if ever, used in bridge design even though there are provisions for its use in the AASHTO Bridge Specifications. Because of their relationship in this instance, the discussion of the wide stringer spacing has been combined with that of the two-way reinforced concrete deck. The design calculations for a two-way slab were in accordance with the current AASHTO Bridge Specifications.

The section of bridge to be discussed is a 3-span continuous unit (60 ft-60 ft-60 ft), which is part of a bridge 822 ft-3 in. long. This structure was to be located in an all-directional interchange where two Interstate Highways intersect (see Fig. 1). The roadway width curb to curb is 30 ft-0 in. and the design loading is H20-S16 1957, PPM 20-4 (see Fig. 2).

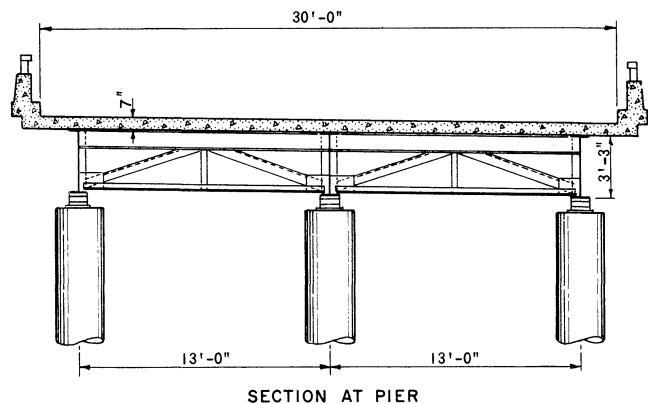


Fig. 2. Section through the deck at pier. Stringers shown are plate girders with cross-frames at 15 ft-0 in. centers. On WF stringers, simple WF diaphragms are used.

**The Economy of Wide Stringer Spacing**—As a result of using a two-way slab, one or possibly two additional lines of cross-frames or diaphragms are required per span and the weight per foot of these members is usually increased 30 to 40 percent. However, the total number of cross-frames or diaphragms required is reduced about 30 percent, meaning that there are about 30 percent fewer units to fabricate and erect. The slab concrete and reinforcing steel quantities generally increase by an amount which depends on the type of slab and the stringer spacings being compared. The stringer steel quantity and number of bearings are reduced, the amount again depending on the stringer spacing being compared and, since there are less units to erect with wide stringer spacing, the erection costs are reduced. Lastly, the pier costs are usually lower for a two-way slab design because the cap beam may be omitted.

A complete comparison of the affected items for two designs is shown in Table 1. The quantities for the two-way slab design do not include the concrete and rein-

forcing steel quantities in the curbs and parapets since they would be the same in both designs. For the piers, only the concrete and reinforcing steel quantities for the 2 ft-6 in. diameter pier shafts, which directly support the stringer at the interior reaction points, are included in the table. The pier foundation quantities have been omitted from the comparison because the quantities in the two designs are approximately equal.

The quantities for the one-way slab design are based on the use of 5 stringers spaced at 6 ft-9 in., a 6½ in. thick slab, and piers composed of 2 ft-6 in. wide by 4 ft-0 in. deep cap beams supported on 2 ft-6 in. diameter shafts.

A noteworthy consideration that is illustrated in Table 1 is the matter of the additional earthwork required to permit the use of a plate girder with a total depth of a little less than 42 in. compared to the 30 in. WF section with cover plates. For many bridges with a structural depth limitation the increased depth may not be available. However, where this limitation does not exist the economic depth should be used, since dirt is relatively inexpensive and the reduction in the cost of the superstructure and piers usually more than offsets the additional cost for the earthwork. In the portion of the bridge presented in this paper there was an available structural depth of about 6 ft, which was more than enough to provide an economical depth plate girder. Nevertheless, in order to obtain an idea of how much additional earthwork is involved in increasing the structural depth 11 in., as was done in using 39 in. plate girders in place of 30 in. WF beams, a set of conditions were hypothesized which would yield close to the maximum amount of additional earthwork that would be necessary to provide 11 in. more structural depth. The design speed on the highway of which the bridge is a part was assumed to be 60 mph, the maximum grade 3 percent, and the minimum vertical clearance 16 ft-0 in. The roadways crossing each other were assumed to be at the same level as the existing ground and therefore the increases in the roadway elevation would be made with embankment. The roadway width is 24 ft-0 in. and since it is a one way roadway there is a 10 ft-0 in. shoulder on the right and a 4 ft-0 in. shoulder on the left.

Wide stringer spacing will generally diminish the exposed area of steel, thus reducing the painting costs which are both an initial and a continuing cost. In the example shown the cross-frames used with the plate girders contain 30 percent of the total exposed area of steel while the WF diaphragms used with the rolled beams contain less than 15 percent, which is the reason that the two designs used in Table 1 have almost the same exposed areas. In cases where both the wide and normal stringer spacing designs use plate girders or rolled beams the reduction in painting will be consistent with the reduction of steel weight.

Perhaps the clearest approach to the comparison presented in Table 1 is to combine the concrete and reinforcing steel quantities from the slab and piers, since, more often than not, the unit price bids are the same in both locations. Compared in this manner it becomes apparent that for all of the items that are part of the two structures, except reinforcing steel, the cost is less for the 13 ft-0 in. stringer spacing. Including reinforcing steel, the total difference between the two structures is \$3,648, which results in a 12.8 percent saving for the 13 ft-0 in. stringer spacing design on the affected items of the structure. This percent saving would be subject to very little variation for bridges with spans of 60 ft or less, whereas the item of additional earthwork required to increase the structural depth can fluctuate considerably depending on the grades of the intersecting roadways. Occasionally, as in the bridge used as an example in this paper, there is more than enough structural depth in a large portion of the bridge because the grades of the intersecting roadways are controlled at points away from the intersection. In such instances the savings would be the above 12.8 percent of the affected items. However, the situation more commonly encountered is one where some additional earthwork is necessary, such as the situation hypothesized previously in this section, for which additional earthwork has been calculated and shown in Table 1. This amount would be about as much additional earthwork as would normally be required for a two lane bridge crossing another highway. There would be infrequent cases, such as for the bridge on the top level of a three level interchange where more earthwork than shown in Table 1 would be necessary, but generally the quantity will be less. Therefore the savings on the affected items will usually be somewhere between 7 and 12.8 percent in favor of the 13 ft-0 in. stringer spacing. Since the affected items represent about 60 percent of the total cost of the bridge, the savings as it applied to the total cost of the bridge would be between 4.2 and 7.7 percent.

One of the factors that brought about the substantial savings of structural steel in the 13 ft-0 in. stringer spacing design was that composite design was economically feasible for this design while it was not for the 6 ft-9 in. stringer spacing design. This indicates that wide stringer spacing can bring the economy of composite design to more bridges than the conventional spacing.\*

The prices used in the table were obtained from local fabricators and contractors, and from current highway lettings.

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\* At the time of this study (1961) shear connectors were more expensive than they are now (1965). The present practice of the Oklahoma State Highway Department is to use shear connectors on all steel stringer bridges. However, they are of greater value for a wide stringer spacing design than for the normal spacing design.

**The Aesthetics of Wide Stringer Spacing**—In addition to the always important economic considerations, the wide stringer spacing design presents a clean, light, uncluttered appearance for short span bridges by reducing the number of stringers and eliminating the need for cap beams on the piers. The need for improving the appearance of bridges crossing highways has become increasingly apparent in recent years due to the necessity for constructing wide multi-lane roadways. The bridges carrying these wide roadways have tended to create a tunnel effect for the driver on the highway below, and the use of the normal stringer spacing (6 ft-6 in. to 9 ft-0 in.) and long cap beams on the piers has only accentuated this effect. The elimination of the cap beams and reducing the number of stringers should mitigate the tunnel effect and improve the aesthetic quality of highway bridges.

**The Role of Welding**—The importance of arc welded connections in implementing the use of wide stringer spacing and continuity is clearly shown in the comparisons listed in Tables 1 and 2. In the first instance the

conventional design using 6 ft-9 in. stringer spacing requires the use of cover plated 30 WF 108 stringers, while in order to achieve the overall savings that resulted from the use of fewer, but larger stringers, three 39 in. welded plate girders were used, which have composite design only in the end spans. In the second instance, continuity would not be as economical nor as aesthetically desirable without the use of welded splices.

Previous to the development of dependable, economical welded connections the savings achieved in the example shown in Table 1 would not have been possible. A smaller savings would have resulted for the bridge in question from the use of three 36WF in place of the three plate girders. In other cases the optimum savings thus derived, resulted from the use of a larger WF section. This would be the case for continuous span bridges with end spans of less than approximately 60 ft.

In still other cases, the greatest reduction in cost can only be effected through the use of plate girders; such is the case in the example presented in Table 1. It is for these spans that arc welding is an indispensable element for attaining an optimum design. In the wide stringer

**Table 1. 13 ft-0 in. Stringer Spacing with Two-Way Slab vs. 6 ft-9 in. Stringer Spacing with One-Way Slab**

Item	13 ft-0 in. Stringer Spacing				6 ft-9 in. Stringer Spacing			
	Size	Quantity	Unit Cost	Cost	Size	Quantity	Unit Cost	Cost
Structural Steel Fabrication	39 in. pl. girder composite	87,840 lbs	\$0.13/lb	\$11,419	30 WF 108 w/ cover pl. s	125,310 lbs	\$0.1125/lb	\$14,097
Structural Steel Erection		334 man-hrs	6.50/man-hr	2,171		465 man-hr	6.50/man-hr	3,023
Bearings		12	55.00 in place	660		20	50.00 in place	1,000
Slab Reinforcing Steel		34,100 lbs	0.11/lb	3,751		27,660 lbs	0.11/lb	3,043
Slab Concrete	7 in. thick	124.8 cu yd	45.00/cu yd	5,616	6½ in. thick	115.9 cu yd	45.00/cu. yd.	5,216
Pier Reinforcing Steel		2,880 lbs	0.11/lb	317		6,600 lbs	0.11/lb	726
Pier Concrete		21.8 cu yd	42.00/cu yd	916		33.1 cu yd	42.00/cu yd	1,390
Additional Earthwork		4,720 cu yd	0.35/cu yd	1,652				
<b>TOTAL</b>				<b>\$26,502</b>				<b>\$28,495</b>

Percent saving on affected items =  $1,993/28,495 = 7.0$  percent.

**Table 2. 13 ft-0 in. Stringer Spacing—Continuous Beam vs. Simple Beam**

Item	Continuous Beam				Simple Beam			
	Size	Quantity	Unit Cost	Cost	Size	Quantity	Unit Cost	Cost
Structural Steel Fabrication	39 in. pl. girder composite	87,840 lbs	\$0.13/lb.	\$11,419	39 in. pl. girder composite	106,640 lbs	\$0.1275/lb	\$13,597
Structural Steel Erection		334 man-hrs	6.50/man-hr	2,171		240 man-hr	6.50/man-hr	1,560
Bearings		12	55.00 in place	660		18	50.00 in place	900
Expansion Devices		1	600.00 in place	600		2	575.00 in place	1,150
<b>TOTAL</b>				<b>\$14,850</b>				<b>\$17,207</b>

Percent saving on affected items =  $2,357/17,207 = 13.7$  percent.

design presented in Table 1, plate girders using riveted connections would produce little, if any, total saving compared to the conventional design. If, for example, the use of riveted connections increases the total cost for fabrication by 20 percent there would be a \$288 saving in favor of the 6 ft-9 in. stringer spacing design. If for some reason welded connections could not be used in this example, as mentioned in the preceding paragraph, savings could still be achieved with wide stringer spacing by using 36WF beams. However, without low cost, reliable welded flange-to-web and flange-to-flange connections there would even be certain continuous and simple span lengths for which wide stringer spacing and a two way slab could not produce an economical design.

**Continuity for Short Span Bridges**—Unlike wide stringer spacing with a two-way slab design, continuity for short span bridges has found some, although not widespread, acceptance. For bridges with spans of between 60 and 100 ft the use of continuity is not unusual, particularly as the spans approach 100 ft. This was economical practice in the past solely on the basis of the saving in stringer steel, even with the use of relatively expensive riveted connections. Today, with less expensive welded connections, continuity effects an even greater saving in short span bridges, and at the same time the welded connections, particularly the splices, have improved the appearance of the structure. It is because of these two factors, coupled with the reduction of design time and effort brought about by the use of electronic digital computers, that bridge designers are gradually putting continuity to use on bridges with spans of less than 60 ft. The latter trend should become widespread with the realization that in many cases the savings in expansion devices and bearings will be almost as significant as the savings in stringer steel. This has been especially true in recent years with the advent of the improved, but more expensive, finger-type expansion joint with the necessary troughs and downspouting to prevent water from damaging the bearings.\*

**The Economy of Continuity**—For the same span lengths and total length of bridge, continuous spans generally require fewer expansion devices and, for the same stringer spacing, slightly more than half as many bearings as compared to simple spans. This is a consideration that probably has not received too much emphasis, with most of the attention in the continuous to simple span comparison being directed toward the weight saving in the stringers. For bridges with spans of over about 60 ft the latter justifies the most attention,

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\* *Current Oklahoma State Highway Department practice is to use a neoprene compression seal type joint which somewhat minimizes this advantage.*

but as the span lengths decrease the savings in expansion devices and bearings assume greater significance and, as can be seen in the figures shown in Table 2, represent a significant portion of the total savings brought about by continuity.

Continuous spans also substitute one line of diaphragms or cross-frames for two lines at each pier between spans. Although the structural steel weight decreases in continuous spans, the fabrication cost remains about the same and the erection cost increases. On all but the very short spans (40 ft or below) the savings in structural steel weight more than pays for the added erection costs. Because of this, continuous spans of less than 40 ft can only be justified on the basis of the savings in expansion devices and bearings.

To illustrate the cost reductions effected by continuity the comparable quantities of a composite simple beam solution are listed in Table 2 along with the like items from the proposed design. To span 180 ft-0 in. bearing to bearing requires three simple spans of 59 ft-3 in. each, but aside from this slight change the other physical dimensions of the composite simple beam design are the same as in the wide stringer, continuous design from Table 2, including the use of a plate girder built with a 39 in. x  $\frac{3}{8}$  in. web plate. Therefore no reduction in earthwork exists in this example although generally there is a reduction since continuous spans usually require shallower sections than simple spans.

The piers are excluded from the comparison in Table 2, since both designs would use three single shafts at each pier. Actually in the simple beam solution the shafts would have to be at least 3 ft-0 in. in diameter at the top in order to allow for the placement of two bearings there. The cost of the additional concrete would be inconsequential since the labor costs would be almost identical for both size shafts and therefore the only increase in cost is for the added concrete at the price for the material alone, which is about \$15 per cubic yard.

The percent savings effected by continuity in short span bridges would remain approximately as indicated in Table 2 for spans of 60 ft and less; however, the proportion of the saving attributed to bearings and expansion devices would increase as the span lengths decreased. For instance, if instead of three 60 ft-0 in. spans there were three 40 ft-0 in. spans, both the total and the percentage structural steel savings diminish compared to the 60 ft-0 in. span design while the total and percentage savings stay the same for the bearings and expansion devices. Therefore the combined effect is to increase the proportion of the total saving attributed to bearings and expansion devices.\*

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\* *The use of neoprene bearings and expansion joints has tended to reduce the above benefits due to continuity on the shorter spans.*

Since the affected items in this comparison represent about 35 percent of the total cost of the complete bridge, the percent savings measured against the total cost would be about 4.8 percent.

As in Table 1, the prices used in Table 2 were obtained from local fabricators and contractors, and from current local highway lettings.

## **PART II—DISCUSSION OF BRIDGES LET TO CONTRACT**

**The Bids**—Wide stringer spacings along with a two-way reinforced concrete deck were employed on a total of 14 bridges (double bridges at seven locations). In August, 1964, 10 of these structures were let to contract and in September, two more were let. In both instances the successful low bidder was R. R. Tway Inc., of Oklahoma City.

The low bid for the first 10 bridges was \$692,692, which was 14.4 percent under the Engineers Estimate of \$809,735. Eight contractors submitted bids on this work and all were under the Engineers Estimate, the high bidder being 1.2 percent under. The second low bidder was less than \$6,000 higher than the low bidder. The number of bids and the closeness of competition seems to indicate that the contractors anticipated no significant difficulty with the new design.

There were 83,950 sq ft of roadway in the first 10 bridges, which means that the total cost per square foot was \$8.25, of which \$1.61 was for steel piling. This total cost was lower than was predicted by either the Highway Department or the Consultant. The Contractor's unit prices for structural steel, reinforcing steel, and deck concrete were all lower than expected and herein lies a point of discussion and speculation. From the inception of the wide stringer spacing design it was obvious that a large reduction in structural steel and smaller reductions in pier concrete and reinforcing steel would result from this design. On the other hand, the deck concrete and reinforcing steel quantities would be somewhat larger. So great were the reductions in the structural steel quantity that it was felt that, in spite of a reduction in labor for this item, the unit price of structural steel would rise. Further, it was thought that the deck concrete price would also rise due to the increased cost of spanning the wide spacing with deck forms. In the case of reinforcing steel, since this item includes the steel in the deck, piers and abutments, it was difficult to come to any conclusion, but an increase in the unit price would not have been surprising, at least initially, because of the added placement difficulty resulting from having bent bars in two directions in the deck. No change was anticipated in the unit price of the pier concrete. In general, unit prices were expected to rise, if for no other reason than the reduction in magnitude of the items over which the contractor could distribute his indirect overhead, which, of course, could even be increased in quantity by virtue of the design change.

The expected increases have not materialized in bridges let to contract thus far. As a matter of fact, all of the unit prices of major items were below the state average on both lettings. However, on the second letting, the contractor apparently recognized some difficulty with the deck concrete by increasing the unit price by \$2.00 per cu yd more than in the first letting.

So many factors are involved in contractors' bids that it could be misleading to formulate trends from one or two lettings. It is still thought that the unit prices will eventually stabilize at a slightly higher level than has been experienced with closer stringer spacing. However, contractors' ingenuity, which, in the case of the two contracts already let, is considerable, should not be underestimated. This intangible factor greatly influences the low bid on new designs.

All of the 12 bridges are now under construction and no formidable difficulties have arisen. Two more bridges using wide stringer spacing and a concrete deck reinforced in two directions will be let to contract in the near future and these bids should shed some more light on the cost picture.

**Cost Comparisons**—As mentioned earlier in the paper, the bridge, which included the portion studied in Part 1, was redesigned and no direct verification is possible for the preliminary analysis made in Part 1. Ideally it would be desirable to have the contractor submit bids on the two designs. However, some indirect comparisons can be made in two ways. First, as shown in Table 3, the unit prices bid by the successful contractor, except for structural steel, are applied to the pertinent quantities computed in Part 1 for the continuous span design using 13 ft-0 in. stringer spacing. The latter solution uses plate girders and since all of the bridges let to contract used *WF* beams, the unit price for structural steel was increased by \$0.015 over the bid price. In the same table the comparable quantities are shown for a simple beam solution using a 7 ft-0 in. stringer spacing. The unit prices bid by the successful contractor are also applied to these quantities. Consistent with Part 1, the quantities shown in Table 3 do not include pier footings or the slab curbs and parapets.

The structural depth required for the wide stringer spacing design is about 6 in. greater than that required in the simple beam design. The additional earthwork incident to this increased depth requirement has been assumed to be one-half of the amount shown in Table 1 where the structural depth difference was 11 in.

The comparison in Table 3 reveals that the percent savings on the items involved is 25.8 percent in favor of the 13 ft-0 in. stringer spacing and continuous spans over 7 ft-0 in. stringer spacing and simple spans. If, as in Part 1, the items involved are assumed to represent 60 percent of the total cost of the bridge, the percent savings would be 15.5 percent. This figure is somewhat

in excess of the maximum of 12.5 percent predicted in Part 1. An explanation of this deviation can probably be found in two factors—the unexpectedly low unit bid prices and a difference in the methods employed in arriving at the two percentages. The low unit bid prices lowered the denominator of the percentage fraction without proportionately lowering the numerator. As for the percentage determination methods, Part 1 was concerned with two separate comparisons—wide stringer spacing and continuity—while in Table 3 these two considerations are dealt with at the same time. As a result of this method difference, more additional earthwork is required in Table 1 than in Table 3, reducing the net savings in Table 1 as compared to Table 3.

Actually a more meaningful number than a percent saving would be a per square foot difference in cost between solutions. This figure can be developed without considering the percentage of the total bridge cost that the involved items represent. The latter percentage is subject to wide variation, depending a great deal upon the type of foundation supporting the bridge. As can be seen from Table 3 the per square foot cost difference is \$1.58 in favor of wide stringer spacing and continuity. However, as pointed out earlier, the Oklahoma State Highway Department is now using the neoprene compression seal type expansion joint. Since Table 3 quantities are based on the use of the finger type joint, the per square foot cost difference would not now be as much as \$1.58.

In the second comparison, as shown in Table 4, two of the bridges let to contract are compared to an example bridge which uses 7 ft-0 in. stringer spacing and is composed of simple spans of comparable length to the former two. The quantities include the pier footings and the curbs and parapets, except that in the example bridge only one curb and parapet was included. The latter was done because the roadway width of the example bridge was about one-half of the width of the other two bridges. If both parapets were included in the example bridge it would disproportionately increase the per square foot costs of this bridge for comparison with the other two bridges. No quantities for the abutments are included. Additional earthwork was not considered a significant factor in the second comparison because there was only a slight difference in the required structural depths for the three bridges. Except for structural steel, the unit prices used on the example bridge were the same as those used for Bridges 1 and 2. Since the unit price for simple span steel is usually lower than continuous span steel, the unit price was assumed to be \$0.01 lower for the example bridge. All three bridges use WF stringers.

The most obvious fact to be noted in Table 4 is the per square foot cost difference between Bridges 1 and 2 and the Example Bridge. These figures are \$0.92

and \$0.96 respectively and again substantiate the thesis that significant savings can be realized by employing wide stringer spacings and continuity instead of 7 ft-0 in. stringer spacings and simple spans. Although, as pointed out previously, a savings percentage of the total bridge cost is not an accurate indicator, it is of some interest to note that the totals shown for Bridges 1 and 2 represent, respectively, 59 and 63 percent of the total bridge cost. On this basis the percent savings, measured against the total cost of a bridge using 7 ft-0 in. stringer spacing and simple spans, is 9.9 percent for Bridge 1 and 11 percent for Bridge 2.

Finger type expansion devices were used on the bridges shown in Table 4; and, as discussed previously, with the use of neoprene compression seal type expansion joints the per square foot cost difference between the two systems would now be less. However, it is also well to

**Table 3**

3-60 ft simple beam spans—30 ft roadway 5 stringers @ 7 ft-0 in.; 6¼ in. thick floor			
	Quantity	Unit Price	Amount
Structural Steel (36 in. WF)	172,270 lbs	\$ 0.135	\$23,256
Slab Reinforcing Steel	31,050 lbs	0.10	3,105
Slab Concrete	111.1 cu yd	42.00	4,666
Pier Reinforcing Steel	6,600 lbs	0.10	660
Pier Concrete	33.1 cu yd	42.00	1,390
<b>TOTAL</b>			<b>\$33,077</b>

$$\text{Area} = 180(30) = 5400 \text{ sq ft} \quad \text{Cost per sq ft} = \frac{\$33,077}{5,400} = \$6.13$$

3-60 ft continuous plate girder spans—30 ft roadway 3 stringers @ 13 ft-0 in.; 7 in. thick floor			
	Quantity	Unit Price	Amount
Structural Steel (39 in. Pl. Girder)	92,720 lbs	\$ 0.150	\$13,908
Slab Reinforcing Steel	34,100 lbs	0.10	3,410
Slab Concrete	124.8 cu yd	42.00	5,242
Pier Reinforcing Steel	2,880 lbs	0.10	288
Pier Concrete	21.8 cu yd	42.00	916
Additional Earthwork	2,360 cu yd	0.35	826
<b>TOTAL</b>			<b>\$24,590</b>

$$\text{Area} = (180)(30) = 5,400 \text{ sq. ft} \quad \text{Cost per sq ft} = \frac{\$24,590}{5,400} = \$4.55$$

$$\text{Percent savings on affected items} = \frac{\$1.58}{\$6.13} = 25.8 \text{ percent}$$

<sup>a</sup> This quantity includes the weight of the bearings and the expansion devices.

**Table 4**

**BRIDGE NO. 1**  
 61 ft-0 in roadway  
 33 ft-9 in.; 58 ft-6 in.; 33 ft-9 in.  
 continuous spans  
 12 ft-0 in. stringer spacing

	Quantity	Unit Price	Amount
Structural Steel	130,100 lbs	\$ 0.135	\$17,564
Class "A" Concrete	36.0 cu yd	42.00	1,512
Class "A" Concrete Pier Bases	56.0 cu yd	40.00	2,240
Class "AA" Concrete	209.7 cu yd	42.00	8,807
Reinforcing Steel	58,870 lbs	0.10	5,487
<b>TOTAL</b>			<b>\$35,610</b>

Area = 61(127.5)  
 = 7,778 sq ft      Cost per sq ft =  $\frac{\$35,610}{7,778} = \$4.58$

**BRIDGE NO. 2**

61 ft-0 in. roadway  
 44 ft-6 in.; 42 ft-9 in.; 58 ft-6 in.; 41 ft-0 in. continuous spans  
 14 ft-3 in. stringer spacing

	Quantity	Unit Price	Amount
Structural Steel	181,000 lbs	\$ 0.135	\$24,435
Class "A" Concrete	63.6 cu yd	42.00	2,671
Class "A" Concrete Pier Bases	69.9 cu yd	40.00	2,796
Class "AA" Concrete	328.0 cu yd	42.00	13,776
Reinforcing steel	84,840 lbs	0.10	8,484
<b>TOTAL</b>			<b>\$52,162</b>

Area = 61(188.25)  
 = 11,483 sq ft      Cost per sq ft =  $\frac{\$52,162}{11,483} = \$4.54$

**EXAMPLE BRIDGE**

30 ft-0 in. roadway  
 40 ft-0 in.; 50 ft-0 in.; 40 ft-0 in. simple spans  
 7 ft-0 in. stringer spacing

	Quantity	Unit Price	Amount
Structural Steel	94,830 lbs	\$ 0.125	\$11,854
Class "A" Concrete	33.1 cu yd	42.00	1,390
Class "A" Concrete Pier Bases	18.6 cu yd	40.00	744
Class "AA" Concrete	102.6 cu yd	42.00	4,309
Reinforcing Steel	31,750 lbs	0.10	3,157
<b>TOTAL</b>			<b>\$21,454</b>

Area = 30(130)  
 = 3,900 sq ft      Cost per sq ft =  $\frac{\$21,454}{3,900} = \$5.50$

note that the simple spans chosen for comparison are, for the most part, shorter than the continuous spans. If exact simple spans were compared to the continuous spans of Bridges 1 and 2, savings slightly greater than those shown in Table 4 would result.

As a sidelight of Table 4 it is significant to note that there is a per square foot cost difference of \$0.04 between Bridges 1 and 2 in favor of Bridge 2. Because the spans in Bridge 2 are longer than those in Bridge 1, the opposite would be anticipated. The explanation for this unexpected reversal lies primarily in the wider stringer spacing used on Bridge 2. It appears justifiable to conclude that reducing the number of stringers, by using 14 ft-3 in. instead of 12 ft-0 in. stringer spacing, will produce greater economy as long as the curb cantilevers are not thereby significantly increased. The possibility of further reducing the number of stringers for the 61 ft-0 in. roadway was not investigated. It is likely that the Oklahoma State Highway Department in their research and continuing investigations into the use of wide stringer spacing will investigate spacings wider than 14 ft-3 in.

A trend revealed in comparing Tables 3 and 4 that is worthy of comment is the larger savings resulting from the use of wide stringer spacing and continuity for the bridge in Table 3. The spans involved in Table 3 are all 60 ft-0 in. whereas all of the spans considered in Table 4 are less than 60 ft and 7 out of the 10 are less than 50 ft. As pointed out in the discussion of continuity in Part 1, continuity effects increased savings over simple spans as the span lengths become longer. A comparison of the savings per square foot in Tables 3 and 4 reveals that over \$0.60 per square foot more was saved in Table 3 than in Table 4.

**CONCLUSIONS**

The magnitude of the design problem presented is not great, and perhaps it is for this reason that little attention has been given to optimizing and aesthetically improving the design of short span highway bridges. However, the magnitude of the cost of all such bridges to be built in the United States suggests that efforts be directed toward improving their design.

A thorough evaluation of current practice and future possibilities in bridge design and construction led to the following conclusions:

- (1) The use of wide stringer spacings with two-way reinforced concrete decks will generally result in substantial savings in cost.
- (2) Continuous spans, even when the spans are quite short, are generally more economical than simple spans.

Conclusion (1) stems from the idea that both from the standpoint of fabrication and erection it is desirable to have the fewest possible number of stringers supporting the roadway. By doing this, less steel and labor are required in fabrication and there are fewer units to erect. To implement this idea for application to short span bridges, stringers are required that are larger than those used with conventional spacing, and a two-way reinforced concrete deck is needed to prevent the additional cost of the deck from greatly reducing the savings in structural steel. The larger stringers are now economically possible because of low cost, reliable welded flange-to-web and flange-to-flange connections for plate girders and welded cover plate connections for rolled beams. For many span lengths for which *W* beams are used with conventional stringer spacing, plate girders are required with wide stringer spacing, and because the larger stringers are used, composite design was not economically feasible in the 6 ft-9 in. stringer spacing design while it contributed greatly to the savings in the 13 ft-0 in. stringer spacing design.

The basis for conclusion (2) lies not only in the savings in structural steel but in the savings in bearings and expansion devices. The latter is significant for short span bridges where the savings for these items amount to an increasingly larger portion of the total savings as the span lengths decrease. The use of welded connections has contributed greatly toward effecting savings in continuous spans because of the splices and the frequent changes in flange thickness. For the latter welding is particularly important, since riveted or bolted flange connections would increase the structural steel costs to a point where continuity would not be economical for most short span bridges. In addition, welded splices have made continuous span bridges more aesthetically palatable.

As a result of wide stringer spacing a savings of between 4.2 and 7.7 percent can be realized in the total cost of short span bridges and this added to a 4.8 percent saving effected by continuity brings about a savings of between 9 and 12.5 percent, when wide stringer spacing and continuity are used instead of conventional stringer spacing and simple beam spans. Considering the fact that the Bureau of Public Roads estimates that there will be almost 10,000 short span bridges in just the new interstate highway system, the latter savings are quite significant.

The results of two lettings of short span bridges employing wide stringer spacing and continuity substantiate the foregoing conclusions.

Future investigations into the use of wide stringer spacings should consider spacings greater than 15 ft-0 in. It appears likely that wider stringer spacings are justi-

fied as the spans increase in length. In the area of research, the AASHO specifications with regard to the design of two-way slabs should be closely examined. Comparing it to other acceptable methods of analysis, it appears that the AASHO method may be over-conservative. Another area of research that deserves some attention is wheel distribution factors for spans over 12 ft. Most of the research that has been done in arriving at the present distribution factors was directed toward spacings of 6 ft to 9 ft which is the range for what has been the normal stringer spacing. The Oklahoma State Highway Department is presently formulating plans to instrument some of the wide stringer spacing bridges now under construction. Their goal is to gather and evaluate data in the two areas just mentioned, and it is hoped that improved design criteria will be developed.

A development that will inevitably have impact on design using wide stringer spacings is the hybrid girder. Essentially, the structural steel reduction that results from the use of wide stringer spacing evolves from the elimination of inefficiently stressed girder webs. The virtue of the hybrid girder lies in the use of inexpensive, carbon steel in the webs and high strength steel in the flanges where it functions efficiently. The two ideas mutually complement and serve each other. However, deflection criteria becomes an important consideration in the use of both ideas. This criteria influenced the member selection for the two-way slab bridges already let to contract. It is also likely that the design of hybrid girders will be controlled by deflection. Since the modulus of elasticity is not increased along with the allowable stress for high strength steels, deeper girders will be required than would have been had stress alone controlled.

Finally, it should be recognized that the design and plan preparation for a bridge using a two-way slab is more time consuming than for a one-way slab. For instance for the bridge shown in Fig. 1, six sheets were necessary to show the two-way slab details. Only two sheets are necessary for the same bridge with a deck reinforced in one direction.

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